Automatic integrated structural design and optimisation in BIM

By

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A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy at the University of Portsmouth

March 2020

Declaration

The work described in this thesis was carried out in the School of Civil Engineering and Surveying (SCES) at the University of Portsmouth. The work has not previously been accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree. This thesis is the result of the author's own work, except where otherwise stated.

For mom and dad

Acknowledgements

First, I would like to express my deepest gratitude to my first supervisor Dr Sepehr Abrishami that without his help I would never have had the opportunity to start my PhD at the first stage. I would like to thank my second and third supervisors Dr Pasquale Ponterosso and Dr David Begg for all the valuable help and guidance during my PhD.

My sincere and deepest gratitude are due to my parents and brothers whose endless support, love and belief in me gave me the strength and energy to complete this journey. Without the love and support of my family, my PhD would never be possible to complete.

Above all, I would like to thank Maria for her love and constant support from the very beginning of my PhD until the end.

I would like to also acknowledge the support of all the academic staff of the School of Civil Engineering and Surveying (SCES) of the University of Portsmouth.

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List of abbreviation

AEC	**Architectural Engineering and Construction**
AI	Artificial Intelligence
ASCE	American Society of Civil Engineers
CSDO	Conceptual Structural Design and Optimisation
GA	Genetic Algorithm
GD	Generative Design
ICE	Institution of Civil Engineers
IStructE	Institution of Structural Engineers
MDO	Multidisciplinary Design and Optimisation
MMR	Mixed Method Research
RIBA	Royal Institute of British Architects
SDO	Structural Design and Optimisation

Abstract

Despite the unprecedented permeation of Building Information Modelling (BIM) and availability of a wide range of collaboration platforms, architects and structural engineers, for the most part, act as separate teams. Therefore, linking architectural models with those of structural engineers remains a labour-dependent and a cumbersome activity. This research proposed potential solutions to improve the structural design processes at the early stages by integrating architectural and structural models and generating alternative structural models for the same architectural model automatically. The research proposed a framework and a proof-of-concept prototype, which used the architectural model and relevant parametric data as input to design and analyse different parametric structural models through an automatic process. This process helps to reduce the iterative structural design process and improve the collaboration between the structural engineers and architects through automation within the BIM platform. The research leveraged the importance of using automation in the structural design process and the collaboration between structural engineers and other disciplines, particularly with the architects.

The research started with an exploratory approach, using a comprehensive literature review to highlight the existing challenges in the structural design, analysis and optimisation processes, particularly at the early stages. Thereafter, based on the information received from the literature review a Conceptual Structural Design and Optimisation (CSDO) framework was developed to solve the identified challenges. In order to justify the research and validate the conceptual framework, an online questionnaire was distributed between professionally accredited structural engineers of the Institution of Structural Engineers (IStructE), The Institution of Civil Engineers (ICE) and the American Society of Civil Engineers (ASCE). The questionnaire uncovered valuable information about the existing challenges, and potential solutions that justifies the research knowledge gap, and the information obtained helped to improve the framework. Thereafter, an extended framework was developed and aimed at improving the integration and interoperability between architectural and structural model in an automatic process in BIM. Hence, a proof of concept prototype was developed to demonstrate the workability of the extended framework. Various case studies demonstrated the workability of the prototype in different areas and type of structures. Finally, the proof of concept prototype was validated in several semi-structured interviews with the academic staff of the University of Portsmouth and chartered structural engineers in industry with civil and structural engineering backgrounds. Furthermore, a focus group was conducted with six domain experts from the Autodesk research and a development team to validate the prototype and receive feedback for further development and future work.

This research contributes to the field by presenting a novel solution, capable of automated generation of structural design, based on architectural models and design requirements (input data). This research provides a practical demonstration of a fully integrated architectural/structural design system. Moreover, this research contributes to the field by extending the outcomes of existing literature that proposed optimisation of structural design, albeit in one dimension, like shape, topology and size in structural design. The proposed framework and proof of concept prototype considers all the dimensions of the optimisation simultaneously and provides a valuable source of reference for future research in this area.

Chapter 1: **Introduction**

1.1 Background and motivation

Structural design is one of the main parts of building design, which includes roles and definitions of safety, economy and performance of buildings (Issa & Olbina, 2015). The general process of structural design begins with the conceptual design in parallel with design goal requirements including clients demand, scientific and engineering laws (codes), aesthetic requirements of the architectural design (Issa & Olbina, 2015). Furthermore, the conceptual design stage has a significant effect on the project's life-cycle performance of the building (J. P. Basbagill, Flager, & Lepech, 2014), since very important decisions are often made at this stage (Cavieres, Gentry, & Al-Haddad, 2011). These decisions affect the cost, performance, reliability, safety and environmental impact of a product (Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013). Existing literature stated that design decisions account for more than 75% of final product costs (Hsu & Liu, 2000; J. Wang, 2001; J. Wang, 2002). Duffy et al. (2007) argued that 80% of the cost of a product, which is due to poor concept design decisions, could rarely be compensated at the later stages. On the other hand, Chong et al. (2009) stated that even detail design of the highest standards is unable to compensate for a poor design decision made at the conceptual design stage.

Although, Chi et al. (2015) and many other professionals in this area argued the structural design process lacks in terms of flexibility and requires a new workflow to facilitate the tedious and time-consuming process and communication with other design aspects (such as architects) (Díaz, Alarcón, Mourgues, & García, 2017). In this case, the construction industry indicates evidence of the potential of BIM to transform the design methods and construction (L. Chen & Luo, 2014). Existing literature highlighted that structural design and analysis is one of the most required uses of BIM technology (Y. Jung & Joo, 2011). BIM-enabled structural design can be coupled with other disciplines such as architecture and fabrication to facilitate the coordination process (Okakpu et al., 2018). The relationship between architecture and structure is a fundamental aspect of building design. In this process, any failure in the structural analysis needs to be solved by modifying the architectural and/or structural model, redesigning the structural model and reanalysing the model. This repetitive and time-consuming design and optimisation process helps to improve the structural model. Finally, the optimum structural design will be sent for detail design to be used for fabrication and construction.

Optimisation can be described as the process of finding the best solution from a collection of potential alternative solutions. Currently, state of the art technology and optimisation tools equip engineers to generate new, better and economical solutions. In this process, development of fast computers not only improved engineers' performance in the field of design and optimisation but also, increased the speed of the entire process. Structural optimisation is considered as one of the most important and challenging fields in engineering optimisation. Structural optimisation alters the assembly of the structural elements to sustain the applied load in the most efficient arrangement. Development of the computational tools improved the optimisation techniques by handling large-scale optimisation problems. This combination has greatly increased the research in this area. Numerous research investigations have been conducted over the last few decades utilising various methods to optimise structures in terms of weight, cost and strength.

Structural design requires the designers to consider various factor such as strength, cost and at the same time aesthetic requirements for the architectural model. Therefore, structural optimisation includes repetitive and time-consuming process in AEC industry (Allaire, Dapogny, & Frey, 2014; V. Granadeiro, Duarte, Correia, & Leal, 2013a). To some extent, BIM technology has solved the challenges of integration amongst different disciplines. However, there are still issues in this area. Therefore, this research proposes a new framework to facilitate the repetitive process of structural design and design change detection at the early stages. This framework uses automation in the BIM platform to integrate the structural model with the architectural model and updates the structural models according to the changes on the architectural model. This automatic synergy reduces significantly the amount of time and increases the accuracy of structural design. Furthermore, this framework designs and analyses different alternative structural models for the proposed architectural model. This system enables the designers to evaluate and compare various structural design alternatives and improves the decision-making in the optimisation process. Hence, the proposed framework generates conceptual structural design solutions with high strength and economic in a relatively less time and effort. A proof of concept prototype has been developed to demonstrate and evaluate the workability of the framework. The proposed prototype has the potential to be extended and use different methods of optimisations such as Genetic Algorithms (GA) and improve the optimisation process.

1.2 Aim and objectives

The overall aim of this research is to improve the conceptual structural design process by developing a new framework to support the automatic integration between the architectural model and structural model and structural design decision-making at the early stages. The proposed framework facilitate the integration and coordination between architectural design and structural design and improve the optimisation and decision-making process of the structural design at the early stages. To achieve the overall aim, the research objectives have been set as follows:

- **Objective 1: Identify existing challenges during the structural design process:** Ascertain the challenges associated with the structural design and optimisation processes through a comprehensive literature review followed by an online questionnaire

- **Objective 2: Identify the potential solutions:** Investigates how the use of automation and BIM technology can address the identified challenges by integrating the architectural model to the structural model and generate alternative structural solutions for the same architectural model
- **Objective 3: Develop a conceptual framework**: As a potential solution to the identified challenges, develop a schematic flowchart to demonstrate the process of the framework
- **Objective 4: Validate the conceptual framework:** Use an online questionnaire to justify the research and validate the framework. In addition, based on the responses to the questionnaire, modify the framework and develop an extended version
- **Objective 5: Develop a proof of concept prototype:** Use generative design, visual programming tools and FEA tools for structural design and analysis in BIM platform to develop a proof of concept prototype and demonstrate the workability of the proposed framework
- **Objective 6: Validate the prototype**: Use case studies in different interviews and focus groups to demonstrate the workability and generalisability of the proposed proof of concept prototype

1.3 Research methodology

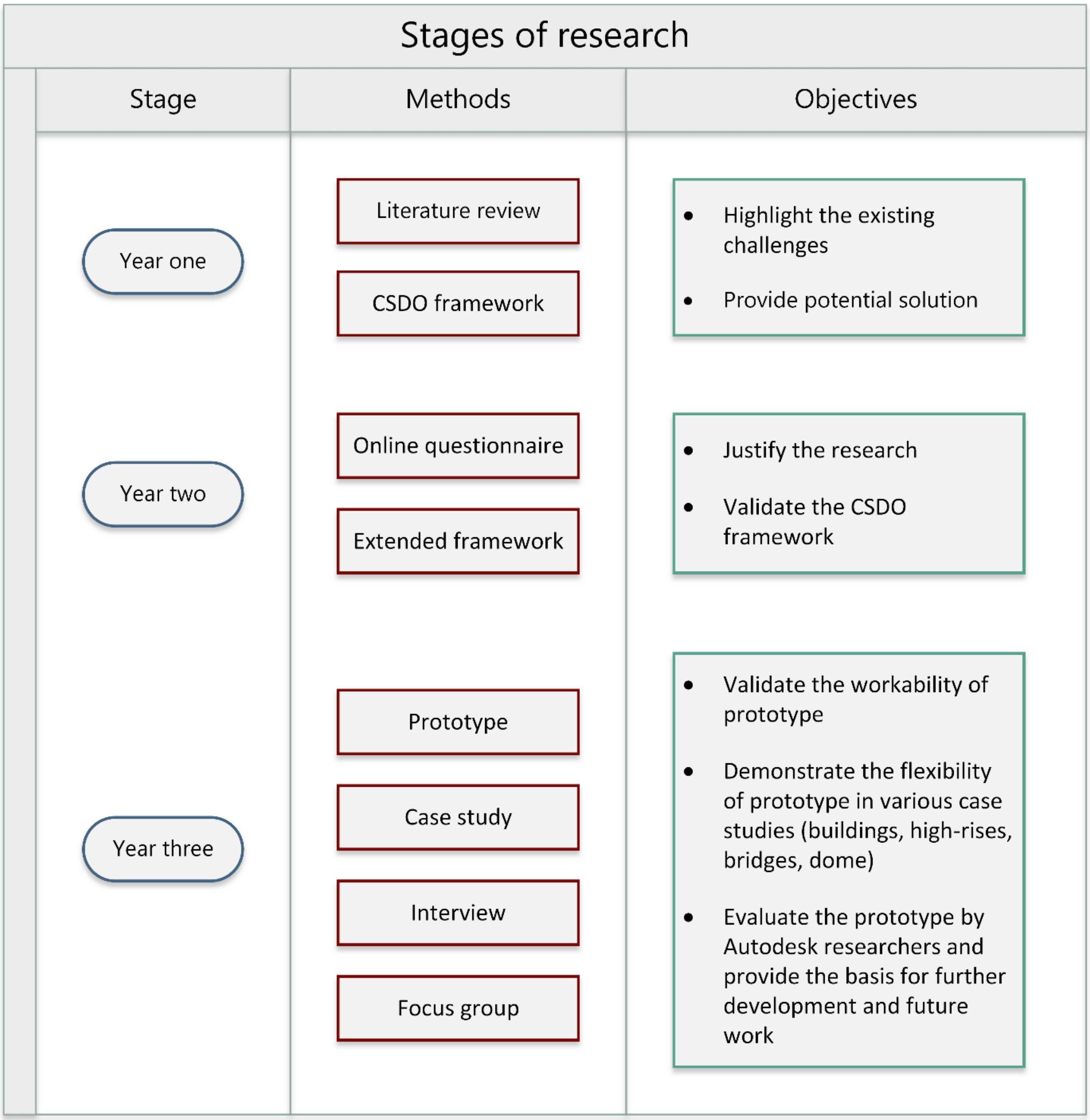

Figure 1: Research development during the three years of research.

The focus of this research is on the automatic integration amongst architectural design and structural design and structural design and optimisation in the BIM platform. Therefore, the research started with an exploratory objective through a comprehensive literature review regarding structural design and BIM to highlight the existing challenges in the structural design process particularly in the BIM platform. This resulted in the identification of challenges during the conceptual structural design process, structural design optimisation and integration amongst architectural models and structural models. Thereafter, various methods were reviewed to select the potential solutions to the existing challenges. This helped to produce the Conceptual Structural Design and Optimisation (CSDO) framework in BIM. In order to justify the research and validate the CSDO framework an online questionnaire was distributed among 354 professionally accredited structural engineers in the UK. The questionnaire received 107 responses (32.22% response rate) from IStructE members (61%), ICE members (17%), ASCE members (7%) and other institutions (15%). The results of the online questionnaire data analysis showed that time consuming structural design and optimisation processes and interoperability between architectural and structural models are the most challenging tasks in the current design process. Furthermore, a considerable number of respondents stated that using automation at the early stage of the structural design in BIM would be a potential solution to the highlighted challenges. In addition, data analysis showed that majority of the respondents generate alternative structural models using trial-and-error methods based on their experience. The majority of the respondents argued that this iterative and time-consuming process prevented them from considering alternative models. Therefore, they tend to design according to previous similar projects or other successful projects. Hence, a considerable number of respondents believed that this is very important and helpful to have a system to generate alternative structural models at the early stage of the structural design process. According to the data analysis of the responses to the online questionnaire the CSDO framework was modified and an extended version was developed. Thereafter, a proof of concept prototype was developed by using Autodesk Revit, Autodesk Robot Structural Analysis (RSA) and Dynamo to demonstrate the workability of the framework and the prototype. In order to validate the workability of the prototype 10 interviews with academic staff and professionally accredited structural engineers were conducted. Furthermore, a focus group with the Autodesk researchers was conducted to evaluate the prototype and achieve feedbacks for future work and further developments.

1.4 Key findings

This research conducted an intensive literature review to highlight the existing challenges and potential solutions to the challenges during the structural design and optimisation processes. Therefore, the first solution was to establish the main focus of the design at the early stages of the project development process to guide decisions as progress is made. This way, professional stakeholders can make changes to the design with less cost and effort at the early stages. The second solution was automatic integration and synergy between architectural design and structural design in BIM platform. In this process, parametric data of the BIM-based architectural model is used to generate and analyse alternative structural model automatically. Therefore, any change in the architectural model updates in the structural model automatically, which significantly reduces the time and human errors during coordination amongst different stakeholders. The third solution was to generate different alternative structural models for the same architectural model. This research provides an automated procedure and computational details in the form of a proof of concept that: binds the architectural models with the structural ones; generates and updates alternatives for the structural model based on input extracted from the architectural model; and provides engineers with an optimum design that fulfils the set criteria. The prototype is designed based on an initial need assessment study (questionnaire) to determine the needs and requirements of practitioners. One of the main needs was an automatic structural optimisation process at the early stages. Therefore, Genetic Algorithms (GA) was chosen as an optimisation method to be implemented in the prototype.

Furthermore, this research would establish a basis for researchers in this field to have better understanding of the structural design and optimisation process specifically in BIM and the existing challenges in this area. In addition, this research highlights the importance of automation in the structural design process and explains how this method can improve the integration between architects and structural engineers and optimisation process

1.5 Structure of thesis

The thesis consists of five chapters and three appendices as following:

Chapter 1: Introduction

This chapter describes the research background and motivation, the research aim and objectives, the research methodology, the key findings and the structure of the thesis.

Chapter 2: Literature review

This chapter provides an intensive literature review for the research and highlights the main existing challenges during the current structural design, analysis and optimisation process. Therefore, it begins with a general introduction about the transformation of the structural design from traditional process to the current process. It explains the importance the interoperability between the architects and structural engineers and details the IStructE plan of work, which is co-ordinated with the RIBA Plan of Work 2020. Thereafter, it focuses on the existent academic literature on the optimisation at the conceptual structural design. Thereafter, it explains Building Information Modelling (BIM) and Artificial Intelligence (AI) as suitable methods to solve the highlighted challenges. Finally, it details the Generative Design (GD) and Genetic Algorithms (GA) as the methods has been used in the proposed prototype for automatic design integration, generation and optimisation.

Chapter 3: Methodology

This chapter proposes the research philosophy and justifies the methodology adopted throughout the research before describing the data collection and analysis methods in details. Thereafter, it describes the data collection and data analysis methods in details and explains validity and reliability of the research. Finally, this chapter presents a summary of the data collection and ethical considerations.

Chapter 4: Framework and prototype development

This chapter explains the entire process of the framework and prototype development. It details how a comprehensive literature review is used to develop the framework and validated through an online questionnaire. The aim of the questionnaire was to justify the research and validate the CSDO framework. Therefore, this questionnaire helped to achieve valuable information about the existing challenges that justify the research knowledge gaps. Furthermore, a considerable number of responses were received suggesting potential solutions to the existing challenges. This information helped to improve the framework and develop an extended version of the Structural Design and Optimisation (SDO) Prototype. This chapter also presents the process of the design and development of the SDO Prototype. It begins with the prototype development using software prototyping in three stage of automatic synergy of the input data from Revit to Dynamo, design, optimisation and evaluation process in Dynamo and design and analysis in Robot Structural Analysis (RSA).

Chapter 6: Discussion, contribution to knowledge and Conclusion

This chapter proposes the main findings of the research and the future application of these findings. In addition, this chapter highlights the main research contributions to knowledge.

Chapter 2: **Literature review**

This chapter provides a comprehensive literature review for the research, aims to highlight the existing knowledge gaps and challenges in the current structural design process, and provides a suitable basis to solve the challenges. This chapter is organised based on the recent evolution in the structural design process and is divided into three main sections including structural design, Building Information modelling (BIM) and Artificial Intelligence (AI).

This chapter begins with a general introduction about the transformation of the structural design from the traditional process to the current process, thereafter; it focuses on the existent academic literature on the conceptual structural design, interoperability and collaboration with architects and optimisation at the early stages. Hence, the research highlights the existing challenges during the iterative and time consuming structural design and collaboration between architects and structural engineers. The focus of the research is on the early stages and provides potential solutions to the highlighted challenges. The next section explains BIM, as a potential solution and platform to solve the highlighted challenges. This section explains the BIM-enabled structural design and the recent development of the integration of BIM and automation for structural design and optimisation. Finally, the third section details the automation and Generative Design (GD) in structural design and explains the recent developments in this area, which is used in this research to facilitate the structural design and interoperability between architects and structural engineers. This section explains tools and methods such as Dynamo, Optimo and Genetic Algorithms (GA), which are used in this research.

2.1 Structural design

Structure has always been one of the main parts of building design, which is ascribed to the roles and definitions of safety, economy and performance of buildings (Issa & Olbina, 2015). From early civilization to the current day, they provide shelter, encourage productivity, embody our culture, and certainly play an important part in life on the planet (Prowler, 2019). At present, buildings provide life support systems, communication and collaboration terminals, education organisations, justice institutions, community spaces, and so much more. They are very expensive to build and also to maintain so that they function effectively during their life cycle (Prowler, 2019).

Structural engineers have a role across the whole life cycle of assets, from project inception and delivery, to operations and eventual decommissioning (Bartley, 2017). Structural design (engineering) includes a wide range of skills and capabilities that apply to different types of projects (Vilutiene, Kalibatiene, Hosseini, Pellicer, & Zavadskas, 2019) from small buildings to large buildings such as high-rises and bridges (Chin, Yoon, Choi, & Cho, 2008). The main concern of structural engineers during structural design, analysis and optimisation is to create strong, economic and practical solutions for material fabrication and actual construction (H.-L. Chi et al., 2015). The general process of structural design begins with conceptual design in parallel with design goal requirements including client demands, scientific and engineering laws (codes), aesthetic requirements of the architectural design (Issa & Olbina, 2015). Although, Chi et al. (2015) and many other professionals in this area argued that structural design process lacks in terms of flexibility and requires a new workflow to facilitate the tedious and time-consuming process and communication with other design aspects (such as architects) (Díaz et al., 2017).

2.1.1The structural design process

According to the definition given by Van Langen & Brazier (2006) the design process provides a description of a design object which satisfies a certain set of criteria and meets a given set of design process objectives. The design process of a building includes several stages as following (Mora, Rivard, & Bédard, 2006):

Project start-up: This stage begins with the purpose of the building and wishes of the client. At this stage, project stakeholders develop a brief by identifying the requirements of the building design and construction through consultations (Gervásio, Santos, Martins, & Simões da Silva, 2014).

Concept design: This stage provides initial design concepts for the building and estimates general schematic drawings and layouts for early project configuration. This stage includes choosing preliminary materials, deciding on the overall structural form of the building, generating an approximate dimensional layout, and considering alternative solutions (Soibelman & Pena-Mora, 2000).

Preliminary design: This stage refines the schematic design and estimates the main quantities for the project (Gervásio et al., 2014).

Detail design (developed design): The schematic design moves to this stage to provide all the required information for implementation in construction through iterative evaluation (Gervásio et al., 2014).

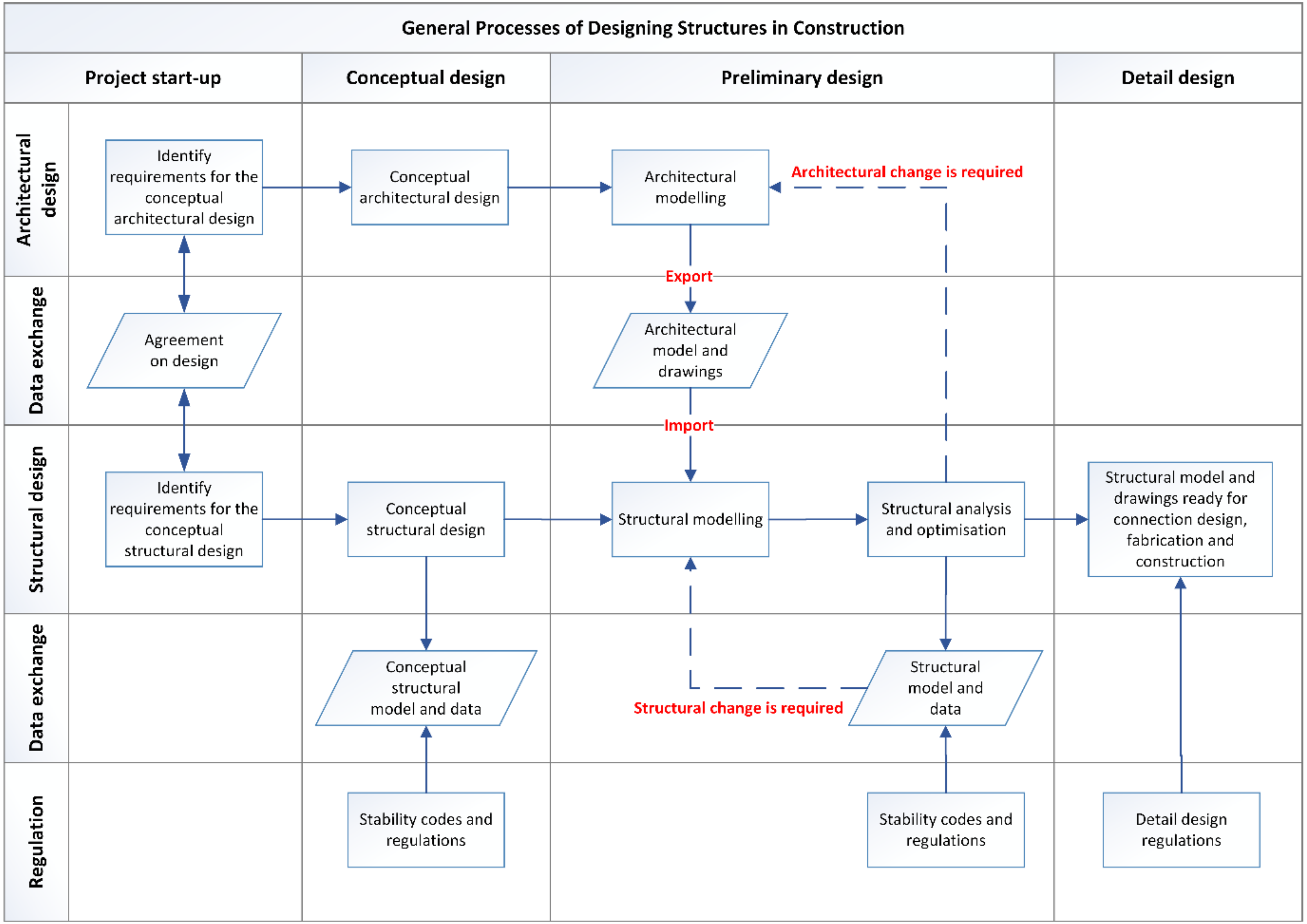

Figure 2: Cross-functional flowchart for a typical structural design process (H. L. Chi, Wang, & Jiao, 2015)

Figure 2 demonstrates a typical structural design process, which begins with the project start-up, where the client proposes the type and purpose of the building. Taking into consideration the clients' design requirements and design themes, architects and structural engineers begin to draft design solutions. After constant collaborations and evaluations between the different stakeholders of the project, the conceptual structural design will be proposed to be confirmed by all the stakeholders. Once the conceptual model is proved to be feasible, the preliminary stage begins with a time-consuming and iterative process design and collaboration between architects and structural engineers. At this stage, architectural models and drawings are used for the structural design by converting the architectural model to structural components such as beams, columns, joists, floors etc. Thereafter, the structural model will be analysed to evaluate the strength of the proposed structure by using relevant national codes and regulations (British Standards, Euro Codes, ASHTO, etc.). At this stage, the design can be improved through iterative optimisation processes. The experience of the structural engineers plays a critical role in the optimisation process and the decision on the superior design solution. In this process, any failure in the structural elements needs to be addressed by changing the structural element or adjustment in the architectural and/or structural model, remodel, reanalyse and redesign the structural model. Often structural design optimisation processes are iterative and time consuming and once the design objectives are achieved they end (H.-L. Chi et al., 2015). Finally, the chosen structural design will be sent for detail design and fabrication.

2.1.1.1 Interoperability between structural engineers and architects

According to Issa and Olbina (2015), traditionally, there are three types of design firms: strictly architectural firms, architectural and engineering firms, and strictly engineering firms. In the architectural firms, the focus is only on the design of buildings and outsource engineering expertise. In the architecture and engineering firms' the focus is on the architectural design, but they also employ structural engineers for their projects to approve the architectural design. The majority of these firms waste considerable time coordinating information exchanges and collaborating with client, architects, engineers, fabricator, etc. (Saeed Banihashemi, Tabadkani, & Hosseini, 2017). These fragmented coordinating information exchanges include sending back and forth 2D or 3D CAD drawings and reports from early stages to the detail and fabrication stages (Issa & Olbina, 2015). The "National Institute of Standards and Technology" reported that 'Cost Analysis of Inadequate Interoperability' in the U.S. Capital Facilities Industry, indicates billions of dollars are wasted annually due to these fragmented coordinating information exchanges (Gallaher, O'connor, Dettbarn, & Gilday, 2004). Many researchers believe that improving the interoperability amongst different disciplines can provide efficient progress in the AEC industry (Díaz et al., 2017; V. Granadeiro, Duarte, Correia, & Leal, 2013b; Shea, Aish, & Gourtovaia, 2005).

The roles of the structures are constantly changing to meet the aesthetic requirements in addition to the strength. Furthermore, cost and time of the building design has become as complex as its design (Prowler, 2019). This progressive complexity of the building design requires an efficient system for different disciplines to collaborate. Gerold (2019) stated that integrative structural design requires simultaneous collaboration to accomplish the design objectives. Furthermore, Pezeshki and Ivari (2018), Sarkisian (2012) and W. Charleson (2015) argued that structural designs must be integrated with the other disciplines like the architects and engineers of different building services. Therefore, design professionals (such as architects and structural engineers) strive for a balance between various and often conflicting goals (Beghini et al., 2014). The complexity of the structural design and the required combination of many disciplines and the variety of communication channels highlights the need to have a reliable exchange platform (Oraee, Hosseini, Papadonikolaki, Palliyaguru, & Arashpour, 2017). Buckminster Fuller is one of the architects whose name is most often connected with architecture, structure and mathematics in the 20th century (Krausse & Lichtenstein, 2000). He believed that ‘synergy’ is the only word in our language that means the behaviour of whole systems is unpredictable if the behaviour of their parts are taken separately (Edmondson, 2012). To Fuller, synergy meant two or more things working together to achieve results greater than they could achieve by themselves (L. Cantor, 2019). Moreover, N. Nawari and Kuenstle (2015) believed that architecture intermixes with the history of mathematics, philosophy and engineering at different levels and designers have adopted concepts from various disciplines to improve their own performance. Therefore, the relationship between architecture and structure is a fundamental aspect of building design, which requires new methods to solve technical, scientific and artistic challenges (Hurol, 2014; Issa & Olbina, 2015). There is considerable research in this area such as (Khan, 2004), (William Addis, 2007), (Schueller, 2008), (Billington, Doig, & Guthrie, 2003), (Sandaker, 2007), (N. O. Nawari, 2011) etc. The common criterion of these researches is that the architecture and structure are inseparable. According to Nervi (1965) architecture cannot be based only upon aesthetic criteria and the structure needs to be stable and efficient in terms of achieving maximum results with minimum materials.

2.1.1.2 Plan of work

Collaboration between architects and structural engineers can provide design solutions greater than the sum of the individual solutions (RIBA, 2019). The IStructE plan of work encourages to use precisely managed process during the development of a project to promote collaborative working between different disciplines to provide better solutions (The Structural Plan of Work 2020: Overview and Guidance, 2020). The IStructE plan of work co-ordinated with the RIBA Plan of Work 2020 and help clearly explain the role of the structural engineers on building projects, and delivering proficiencies and precision for clients (IStructE, 2020). IStructE plan of work includes eight primary stages, representing the full cycle of a building project and purposefully compliment those used in the RIBA plan of work 2020. Table 1 shows an overview of the eight stages of both plans of work RIBA and

IStructE together to demonstrate the close relationship between the architects and structural engineers. The focus of this research is on the stage 2 (Concept Design) and the stage 3 (spatial coordination). At stage 2 (Concept Design) architects propose the conceptual design incorporating strategic engineering requirements and aligned to cost plan project strategies and outline specifications and confirm with the client (RIBA, 2020). On the other hand, at this stage the structural engineers prepare the conceptual structural design and define the shape of the structure and integrated with the architects (IStructE, 2020). This stage represents the start of the design process and the development of the design to align with the project brief (*The Structural Plan of Work 2020: Overview and Guidance*, 2020). At stage 3 (spatial coordination) architectural and engineering information spatially coordinated to create a single solution aligned to the project brief, cost plan and project strategy (*The Structural Plan of Work 2020: Overview and Guidance*, 2020). Therefore, this research proposed a system, which enables these two disciplines integrate automatically and save time and effort. In addition, the proposed system generates alternative structural models based on the information and requirements of the architectural model (input data). Hence, structural engineers select the most suitable alternative conceptual structural model at the early stages of design before technical design begins (stage 4).

	Stage 0: Strategic Definition
RIBA	The best means of achieving the client requirements confirmed
IStructE	Client's main requirements defined
	Stage 1: Preparation and Brief
RIBA	Project Brief approved by the client and confirmed that it can be accommodated on the site

IStructE	Project feasibility confirmed and initial Project Brief defined. Related information collated and prepared to enable the project to progress
	Stage 2: Concept Design
RIBA	Architectural Concept approved by the client and aligned to the Project Brief
IStructE	Architectural and engineering concept information prepared and developed to meet the Project Brief
	Stage 3: Spatial Coordination
RIBA	Architectural and engineering information Spatially Coordinated
IStructE	Architectural and engineering information Spatially Coordinated between disciplines into a single solution aligned to the Project Brief, Cost Plan and Project Strategies
	Stage 4: Technical Design
RIBA	All design information required to manufacture and construct the project completed
IStructE	Architectural and engineering technical design finally coordinated and completed to assemble and construct the project
	Sub-stage 4.5: Production Design
IStructE	Engineering information, including specialist sub-contractors' technical information, prepared to enable the manufacture, assembly and construction to proceed
	Stage 5: Manufacturing and Construction

RIBA	Manufacturing, construction and Commissioning completed
IStructE	Manufacturing, assembly and construction completed
	Stage 6: Handover
RIBA	Building handed over, Aftercare initiated and Building Contract concluded
IStructE	Project handed over, defects rectified and initial Aftercare completed
	Stage 7: Use
RIBA	Building used, operated and maintained efficiently
IStructE	Facilities and asset management. Post Occupancy Evaluation of building performance in use as required

Table 1: Overview of eight stages of the RIBA and IStructE plan of work 2020.

The Institution of StructuralEngineers

The Structural Plan of Work 2020

v1.0 (26/04/20)

	0 Strategic Definition'	1 Preparation and Brief'	2 Concept Design'	3 Spatial Coordination'	4 Technical Design'	4.5 Production Information	5 Manufacturing and Construction'	6 Handover'	7 Use'
	Briefing		**Design**				**Delivery**		**Evaluation**
Overview'	Client's key requirements defined	Project feasibility confirmed and initial Project Brief defined. Related information collated and prepared to enable the project to progress	Architectural and engineering concept information prepared and developed to meet the Project Brief	Architectural and engineering information Spatially Coordinated between disciplines into a single solution aligned to the Project Brief, Cost Plan and Project Strategies	Architectural and engineering technical design finally coordinated and completed to assemble and construct the project	Engineering information, including specialist sub-contractors' technical information, prepared to enable the manufacture, assembly and construction to proceed	Manufacturing, assembly and construction completed	Project handed over, defects rectified and initial Aftercare completed	Facilities and asset management. Post Occupancy Evaluation of building performance in use as required
Contingency Assessment			Appropriate to a design contingency of 20 - 25%	Appropriate to a design contingency of 10 - 15%	Appropriate to a design contingency of 5 - 10%	Appropriate to a design contingency of 2 - 5%			
Design	Contribute to preparation of Client Requirements	Contribute to preparation of Project Brief Contribute to the Site Information Identify survey information required and provide survey scopes Identify structural constraints Identify information required for structural design	Prepare the structural concept design defining the scope, scale and form of the structure, and integrated with the other design disciplines Review survey information and identify any additional surveys required and provide survey scopes Develop, review and assess structural options Define structural design standards and criteria to be used for design, including: - Loading (static and dynamic) - Durability and design life - Fire resistance (in relation to the fire strategy) - Ground movements - Thermal movements - Serviceability criteria (including deflection and vibration criteria) - Embodied carbon targets Define structural grids and structural zones Develop foundation strategy Consider strategy for in use, maintenance and deconstruction	Develop the structural design for defining the detailed form and function of all components in terms of overall size, typical detail, performance and outline specification Spatially coordinate the structural design and integrate with the architectural and other design disciplines Prepare calculations in sufficient details to facilitate and verify design solutions Confirm structural grids and structural zones Develop strategy for in use, maintenance and deconstruction Design for economy of materials by sufficiently detailed analysis to ensure elements fulfil their role safely but without needless use of excess material Design for load conditions and load combinations that can be justified on current knowledge of intended use and ensure that the client is aware of these	Prepare Structural Technical Design Details and designs of specialist structural contractors coordinated and integrated into the structural design Prepare full setting out information for all structural items, fully coordinated and integrated with other design items Review Contractor Designed Items and ensure that they are integrated in the structural design Confirm strategy for in use, maintenance and deconstruction	Development and review of temporary works designs	Review temporary works designs		
Interface		Contribute to the development of the Responsibility Matrix Assist in the development of the Project Information Requirements (PIR) Identify adjoining landowners' issues	Review, update and confirm agreement of the Responsibility Matrix Provide information for preparation of Cost Plan and Project Strategies Undertake third party consultations	Establish critical construction details, tolerances, performance tolerances and anticipated movements (static and dynamic), defining critical coordination clearances Below ground services and structure integration Undertake third party consultations	Liaise with specialist sub-contractors as necessary Integration of builders work items into structural design Undertake third party consultations	Review of Contractor's proposed method statements or sequencing proposals for complex or critical structural items			Conclude as required activities listed in Plan for Use Strategy including Post-occupancy Evaluation, review of Project Performance, Project Outcomes and Research and Development aspects.
Construction			Identify Contractor Designed Items Consider constructability issues	Provide Performance Specification for Contractor Designed Items Develop constructability issues and highlight any project specific criteria including critical temporary works requirements	Develop temporary works briefs	Manufacturing and construction information (e.g. reinforcement drawings and bar bending schedules, steelwork fabrication drawings) prepared	Resolve site queries Undertake site visits and inspections to review the progress of the works on site 'As-constructed' information, prepared by relevant parties as agreed/defined in the scope of services		
Management		Provide information for and contribute to Project Execution Plan as required Identify and define statutory requirements relevant to the structural design	Consider and contribute to H+S risk management process and develop proposals for risk mitigation Assist Lead Designer with preparation of stage Design Programme	Develop and contribute to H+S risk management process and develop proposals for risk mitigation Assist with the implementation of Change Control Procedures Assist Lead Designer with preparation of stage Design Programme Provide information for preparation of Cost Plan, Project Carbon Tracking and Project Strategies	Develop and contribute to H+S risk management process and develop proposals for risk mitigation Assist Lead Designer with preparation of stage Design Programme Provide information for preparation of Cost Plan and Project Strategies		Review quality records and assist in the resolution of manufacture and construct non-conformities Assist with the preparation of Building Log Book, O&M Manual etc as required	Undertake tasks listed in Plan for Use Strategy Contribute to post-contract reviews and certification Contribute to Lessons Learnt exercises	Undertake tasks listed in Plan for Use Strategy
Sustainability	Support the strategic definition of the project in relation to the client's needs, including the appropriateness of development versus upgrading or extending existing buildings as an alternative to demolition	Support the client in developing a brief with clear sustainability outcomes that will contribute positively towards mitigating Climate Breakdown Identify potential Climate Change impact on the design requirements for the project over its intended life span to ensure resilience	Evaluate options to lower the embodied carbon within the structural design, including material choices and efficient building layout Agree embodied-carbon tracking terms and targets Consider design for deconstruction and re-use	Assist with the establishment of a method of carbon tracking that is compatible across the whole design team Track embodied carbon in structural components to an accepted and agreed standard and level of detail Design to achieve the embodied carbon targets agreed at Stage 2	Develop the detailed structural design to minimise wasteful use of resources, both in quantum and in detail Provide Structural Sustainability Report	Update Structural Sustainability Report from Stage 4 based on more detailed development of the Technical and Production Design	Collaborate with clients, architects, engineers and contractors to further reduce construction waste Ensure that the Structural Sustainability Report requirements, including the embodied structural carbon targets, are achieved through construction Assist in the preparation of overall sustainability certification	Document the project Sustainability Targets and achievements (including Carbon) and share on an open source basis	Support as appropriate a Post-occupancy Evaluation to understand the embodied and operational resource use, and use the results to inform future work As required, undertake a Post-occupancy Evaluation to correlate designed performance and achieved performance of the structural systems Share this data, knowledge and research on an open source basis
Statutory Requirements*		CDM requirements including appointment of Principal Designer	CDM requirements including Designer duties				Assist with the preparation of the Health and Safety File information	Update Health and Safety File information if required	
			Preliminary Building Regulations discussions		Submission of information to demonstrate compliance with Building Regulations				
			Provide information to support Party Wall Agreements, and other relevant Approval in Principle (AIP) and statutory requirements and agreements						
			Planning Application support						
Stage Outputs Deliverables at end of stage		Initial Project Brief Site Information Structural Constraints Structural Survey Reports Climate Change Impact Statement	Basis of Structural Design Deliverables List Initial Structural Drawings / Model Concept Structural Sustainability Report	Structural Drawings / Information Model spatially co-ordinated Movement and Tolerances Report Outline Structural Specification Performance Specification for Contractor Design Items Outline Structural Sustainability Report	Structural Drawings / Information Model suitable for manufacture and construction Structural Specification Structural Sustainability Report		Handover documentation		
Information Exchanges		Prepare Exchange Information Requirements (EIR)	Review Exchange Information Requirements (EIR) and contribute to BIM Execution Plan (BEP)	Preliminary clash detection and resolution	Clash detection and clash resolution		BIM Handover deliverables		
Collaboration Requirements			Integrate with appropriate disciplines including Lead Designer to confirm spatial layouts, structural grids and zones	Integrate with design team to assist with the spatial coordination of items	Detailed integration with specialist sub-contractor design and final integration of all design items				
Design Assurance		Initial review of key structural engineering risks impacting on successful delivery of project	Design review of structural principles including stability, loading criteria, load paths, structural assumptions and risks	Detailed reviews of structural principles, stability, soil-structure interaction, load paths, material specifications	Detailed calculation checking (including third party checking if required) Review of specialist sub-contractor designs	Review and checking of manufacturing and construction information	Review of manufacture and construct quality testing and conformity with design specification. Snagging and structural defects		

NOTES:

The IStructE Structural Plan of Work 2020 has been developed to coordinate and integrate with the RIBA Plan of Work 2020. It is intended that the Structural Plan of Work provides a complementary framework for organising the structural engineering requirements for building projects to provide structural engineers, clients and other design disciplines with a more collaborative and unified approach to the process planning of projects.

Reference: 'RIBA Plan of Works 2020

Stages 0 and 1 comprise the Briefing portion where the initial brief and project requirements are determined.

Stages 2, 3 and 4 comprise the Design portion of the project where all of the information required for the Manufacturing and Construction of the project is prepared. A sub-stage 4.5 is included within the Plan of Work for the preparation of the production information required to undertake the construction works. This sub-stage is frequently undertaken by a range of designers and specialist sub-contractors.

Stage 5 starts when the Contractor takes possession of the site (or instruction to commence production in the case of off-site manufacture) and hence there is likely to be significant overlap between Stage 4, Stage 4.5 and Stage 5 for the various structural aspects of the project (e.g. pile design and bending schedules completed and piles installed on site prior to secondary steelwork being fully detailed). Stage 6 starts at Practical Completion and finishes at the end of the defects liability period.

A Responsibility Matrix should be prepared early in the project to identify who is responsible for the various aspects of the structural works, at what levels of details and at which stage in the project.

Note that there may be different organisations appointed for different stages of the project (e.g. one organisation is appointed for Stages 0 and 1, but then a separate organisation is appointed for Stages 2-6), or that separate appointments may be made for the different stages (e.g. a separate appointment is used for Stage 7 services).

*Statutory requirements are given in the Plan of Work as generally applies within the UK. The section should be adapted and amended to suit the relevant requirements of the jurisdiction for the project.

Figure 3: IStructE Plan of Work 2020 (IStructE, 2020)

RIBA Plan of Work 2020

The RIBA Plan of Work organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages. It is a framework for all disciplines on construction projects and should be used solely as guidance for the preparation of detailed professional services and building contracts.

Stage Boundaries:
Stages 0-4 will generally be undertaken one after the other.
Stages 4 and 5 will overlap in the Project Programme for most projects.
Stage 5 commences when the contractor takes possession of the site and finishes at Practical Completion.
Stage 6 starts with the handover of the building to the client immediately after Practical Completion and finishes at the end of the Defects Liability Period.
Stage 7 starts concurrently with Stage 6 and lasts for the life of the building.

Planning Note:
Planning Applications are generally submitted at the end of Stage 3 and should only be submitted earlier when the threshold of information required has been met. If a Planning Application is made during Stage 3, a mid-stage gateway should be determined and it should be clear to the project team which tasks and deliverables will be required.
See Overview guidance.

Procurement:
The RIBA Plan of Work is procurement neutral – See Overview guidance for a detailed description of how each stage might be adjusted to accommodate the requirements of the Procurement Strategy.
ER Employer's Requirements
CP Contractor's Proposals

Projects span from Stage 1 to Stage 6; the outcome of Stage 0 may be the decision to initiate a project and Stage 7 covers the ongoing use of the building.

	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
Stage Outcome at the end of the stage	The best means of achieving the Client Requirements confirmed If the outcome determines that a building is the best means of achieving the Client Requirements, the client proceeds to Stage 1	Project Brief approved by the client and confirmed that it can be accommodated on the site	Architectural Concept approved by the client and aligned to the Project Brief The brief remains "live" during Stage 2 and is derogated in response to the Architectural Concept	Architectural and engineering information Spatially Coordinated	All design information required to manufacture and construct the project completed Stage 4 will overlap with Stage 5 on most projects	Manufacturing, construction and Commissioning completed There is no design work in Stage 5 other than responding to Site Queries	Building handed over, Aftercare initiated and Building Contract concluded	Building used, operated and maintained efficiently Stage 7 starts concurrently with Stage 6 and lasts for the life of the building
Core Tasks during the stage Project Strategies might include: – Conservation (if applicable) – Cost – Fire Safety – Health and Safety – Inclusive Design – Planning – Plan for Use – Procurement – Sustainability See RIBA Plan of Work 2020 Overview for detailed guidance on Project Strategies	Prepare Client Requirements Develop Business Case for feasible options including review of Project Risks and Project Budget Ratify option that best delivers Client Requirements Review Feedback from previous projects Undertake Site Appraisals No design team required for Stages 0 and 1. Client advisers may be appointed to the client team to provide strategic advice and design thinking before Stage 2 commences.	Prepare Project Brief including Project Outcomes and Sustainability Outcomes, Quality Aspirations and Spatial Requirements Undertake Feasibility Studies Agree Project Budget Source Site Information including Site Surveys Prepare Project Programme Prepare Project Execution Plan	Prepare Architectural Concept incorporating Strategic Engineering requirements and aligned to Cost Plan, Project Strategies and Outline Specification Agree Project Brief Derogations Undertake Design Reviews with client and Project Stakeholders Prepare stage Design Programme	Undertake Design Studies, Engineering Analysis and Cost Exercises to test Architectural Concept resulting in Spatially Coordinated design aligned to updated Cost Plan, Project Strategies and Outline Specification Initiate Change Control Procedures Prepare stage Design Programme	Develop architectural and engineering technical design Prepare and coordinate design team Building Systems information Prepare and integrate specialist subcontractor Building Systems information Prepare stage Design Programme Specialist subcontractor designs are prepared and reviewed during Stage 4	Finalise Site Logistics Manufacture Building Systems and construct building Monitor progress against Construction Programme Inspect Construction Quality Resolve Site Queries as required Undertake Commissioning of building Prepare Building Manual Building handover tasks bridge Stages 5 and 6 as set out in the Plan for Use Strategy	Hand over building in line with Plan for Use Strategy Undertake review of Project Performance Undertake seasonal Commissioning Rectify defects Complete initial Aftercare tasks including light touch Post Occupancy Evaluation	Implement Facilities Management and Asset Management Undertake Post Occupancy Evaluation of building performance in use Verify Project Outcomes including Sustainability Outcomes Adaptation of a building (at the end of its useful life) triggers a new Stage 0
Core Statutory Processes during the stage: Planning Building Regulations Health and Safety (CDM)	Strategic appraisal of Planning considerations	Source pre-application Planning Advice Initiate collation of health and safety Pre-construction Information	Obtain pre-application Planning Advice Agree route to Building Regulations compliance Option: submit outline Planning Application	Review design against Building Regulations Prepare and submit Planning Application See Planning Note for guidance on submitting a Planning Application earlier than at end of Stage 3	Submit Building Regulations Application Discharge pre-commencement Planning Conditions Prepare Construction Phase Plan Submit form F10 to HSE if applicable	Carry out Construction Phase Plan Comply with Planning Conditions related to construction	Comply with Planning Conditions as required	Comply with Planning Conditions as required
Procurement Route Traditional	Appoint client team	Appoint design team			Tender	Appoint contractor		Appoint Facilities Management and Asset Management teams, and strategic advisers as needed
Design & Build 1 Stage					ER CP Appoint contractor			
Design & Build 2 Stage			ER	Pre-contract services agreement	CP Appoint contractor			
Management Contract Construction Management			Appoint contractor					
Contractor-led			ER	Preferred bidder	CP Appoint contractor			
Information Exchanges at the end of the stage	Client Requirements Business Case	Project Brief Feasibility Studies Site Information Project Budget Project Programme Procurement Strategy Responsibility Matrix Information Requirements	Project Brief Derogations Signed off Stage Report Project Strategies Outline Specification Cost Plan	Signed off Stage Report Project Strategies Updated Outline Specification Updated Cost Plan Planning Application	Manufacturing Information Construction Information Final Specifications Residual Project Strategies Building Regulations Application	Building Manual including Health and Safety File and Fire Safety Information Practical Completion certificate including Defects List Asset Information If Verified Construction Information is required, verification tasks must be defined	Feedback on Project Performance Final Certificate Feedback from light touch Post Occupancy Evaluation	Feedback from Post Occupancy Evaluation Updated Building Manual including Health and Safety File and Fire Safety Information as necessary

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Core RIBA Plan of Work terms are defined in the *RIBA Plan of Work 2020 Overview* glossary and set in Bold Type.

Further guidance and detailed stage descriptions are included in the *RIBA Plan of Work 2020 Overview*.

Figure 4: RIBA Plan of Work 2020 (RIBA, 2020)

2.1.1.3 Conceptual structural design

According to Pahl et al. (2007) conceptual design is the stage in which the requirements and design objectives (from the start-up stage) are embedded into different conceptual alternative solutions. Thereafter, all the developed alternatives are evaluated and ranked to select the best solution for further improvement (Turrin, Von Buelow, & Stouffs, 2011). O'Sullivan (2002) stated that the conceptual design stage is the product generation process during which designers define certain constraints and statements to generate many alternative solutions. From the methodological point of view, Horváth (2005) defines conceptual design as a creative problem solving process, enabled by human knowledge, intuition, creativity and reasoning.

The conceptual design stage plays a critical role in the project's life-cycle performance of the building (J. P. Basbagill et al., 2014) as the most vital decisions are often made at this stage (Cavieres et al., 2011). These decisions have a significant effect on the cost, performance, reliability, safety and environmental impact of a product (Eadie et al., 2013). It has been estimated that design decisions account for more than 75% final product costs (Hsu & Liu, 2000; J. Wang, 2001; J. Wang, 2002). Moreover, Duffy et al. (2007) stated that 80% of the cost of a product which is due to poor concept design decisions can rarely be compensated at the later stages. Chong et al. (2009) argued that even the highest standards of the detail design is unable to compensate for a poor design decision made at the conceptual design stage. It is, therefore, vital that designers have access to the right tools to support such design activities. Despite the variation amongst design disciplines, there is a common agreement on the relevant importance of the design stage. Figure 5 indicates an overview proposed by three different authors assigned to the conceptual design in terms of the need for a redistribution of the focus knowledge, integration of computational support, and efforts during different stages of design. In this figure, Fabrycky & Blanchard (1991) focused on the need of fundamental knowledge about economics and lifecycle costs during conceptual stages. Wang et al. (2002) emphasised the importance of computational support at the conceptual stage. MacLeamy argued the effect of redistribution of the stakeholders' efforts to improve the outcome of the design process which is the basis of an Integrated Project Delivery (IPD) method (Cavieres et al., 2011). The "MacLeamy Curve" emphasises on the earlier decision making in the design process when there is a high chance of making positive effect and the cost of the changes is minimized (The American Institute of Architects, 2007).

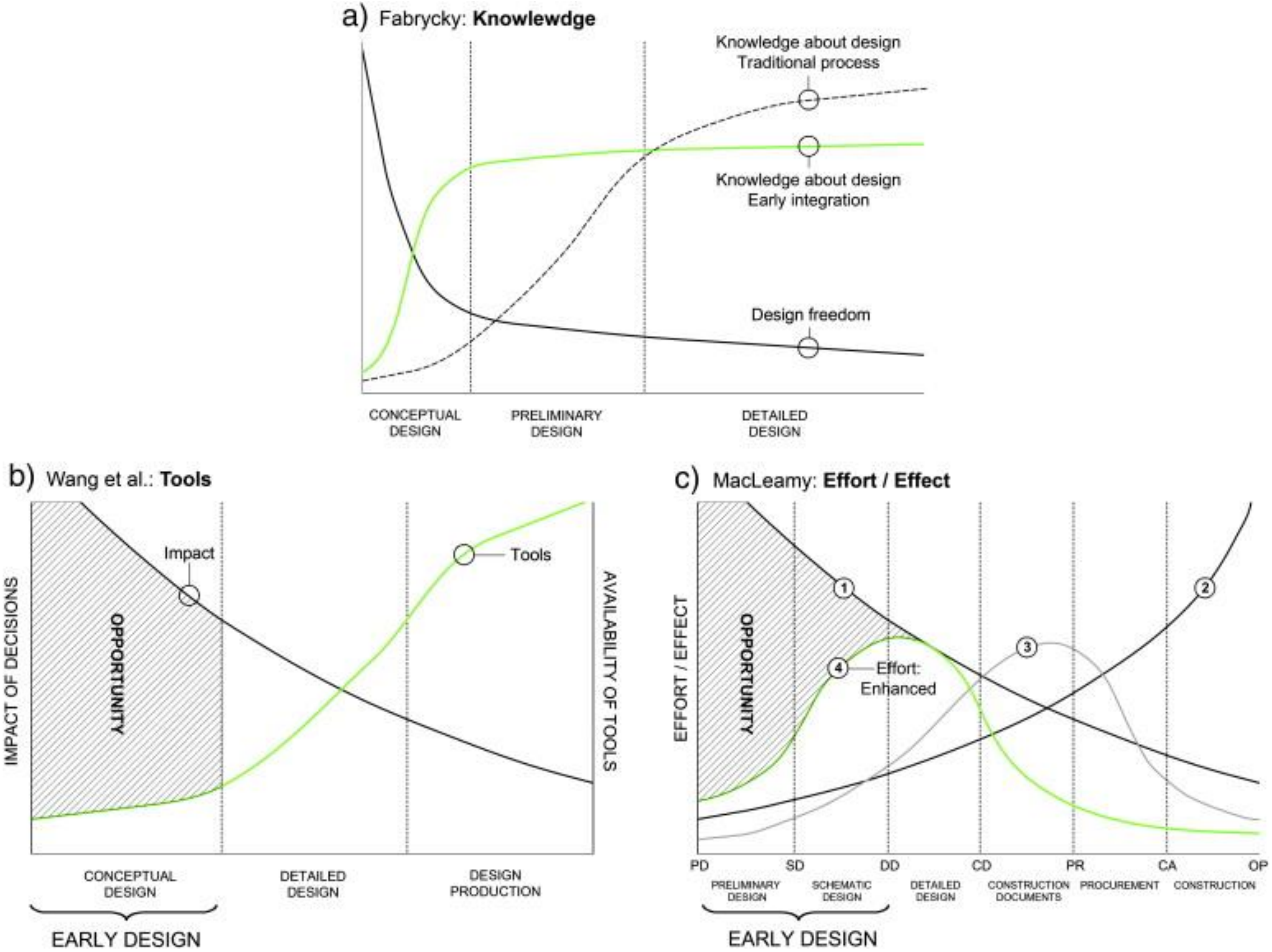


Figure 5: a) relationship between available knowledge and level of design stage in the conventional design approach versus an early integration approach from Fabrycky & Blanchard (1991). *b) potential effect of the computational design tools at the early stages proposed by Wang et al. (2002). c) Refers to "**MacLeamy Curve**" in which curve 1 shows the ability to impact costs and functional capabilities, curve 2 shows the cost of design changes, curve 3 shows traditional design process and curve 4 shows IPD design process.*

The amount of information available at the early stage affects the required time and quality of the whole design process (Nour & Beucke, 2019). Gervásio et al. (2014) argued that, the lack of adequate information at the early stage is the main problem during conceptual design. In conventional practice, architects and engineers have an estimate of the building design and relevant costs, which requires constant collaboration and iterative design and amendment to produce the detail design (Haapio, 2012). According to the American Institute of Architects (2007) the lack of computational tools at the early stage is the main reason of the unresolved issue of effort redistribution in which BIM is the potential solution (Hunt, 2013). BIM is capable of reducing 80% of the time taken to generate a cost estimation and reducing up to 7% in project time (Azhar, 2011). Chi et al. (2015) argued that the immediate influence of the adoption of computer-aided tools at the early stages would be an increase in productivity in design documentation.

There is an increasing research in different areas with the focus on the conceptual design. These areas including ship structural design (Avi, Lillemäe, Romanoff, & Niemelä, 2015) Aircraft Conceptual Structural Design (Horvath, 2019; Schweiger, Cunningham, Dalenbring, Voß, & Sakarya, 2018), machine tool structure design (J. Wang et al., 2017), energy performance assessment (Schlueter & Thesseling, 2009) embodied environmental impacts assessment (J. Basbagill, Flager, Lepech, & Fischer, 2013) assessment of building sustainability (Gervásio et al., 2014). Table 2 indicates example of studies at the conceptual design of buildings. Most of these studies proved that integration of various disciplines at the early stages support the generation of alternatives and/or facilitate the optimisation process.

Reference	Aim	Area
Stromberg et al. (2011)	proposed a pattern gradation method in order to create repetitive schemes	Structural design/Skyscrapers

Dombernowsky and Søndergaard (2009)	Generate topologically optimised building components in pre-stressed concrete	Concrete structures
Beghini et al. (2014)	Connecting architectural and structural design	Architecture and structural design
Aage et al. (2015)	Advanced Topology Optimisation Methods for Conceptual Architectural Design	Architecture and structural design
Barg et al. (2018)	Aims to quickly and accurately estimate the material, fabrication, and erection cost of steel frames	structural design
Brown and Felipe (2016)	Improve the integration of architectural and structural performance in a parametric multi-objective design tool	Architecture and structural design
Granadeiro (2013)	Improve the integration between building envelope shape and energy simulation	Architectural design and energy simulation
Oti & Tizani (2015)	Improve sustainability appraisal of conceptual steel design	Steel design
Donn et al. (2012)	Provide access to the power of detailed simulation tools to solve the problem of needing real information at the early stages	Structural design-energy efficiency
Eleftheriadis et al. (2015)	Reducing the environmental impacts of structural systems through a more efficient use of materials	Structural design-sustainability
Eleftheriadis et al. (2018)	Automate the specification of steel reinforcement to improve the optimisation of reinforced concrete (RC) flat slabs	Structural design- RC
Lim et al. (2018)	Explore the use of BIM and GA to support decision making during building shape optimisation	Architectural design-sustainability
(Donath & Lobos, 2009)	Analyse the problem of the design of envelopes for high-rise isolated residential buildings	Architectural design-High rises
Bianconi et al. (2019)	Aim to develop a cross laminated timber (CLT) model for the Architecture, Engineering, and Construction (AEC) industry	Architectural design

(Oti, Tizani, & Zada, 2014)	proposes a prototype system for appraising the sustainability of design options at the conceptual design stage	Structural Design-Steel Framed Buildings

Table 2: Extant research on the early stage of the building design.

2.1.2Structural optimisation

Structural optimisation methods are most frequently applied to the design of automotive (Großmann, Weis, Clemen, & Mittelstedt, 2020) and aerospace structures (J.-H. Zhu, Zhang, & Xia, 2016) where weight savings are essential. The application of structural optimisation methods in building design is a more challenging proposition (Tsavdaridis et al., 2015). Structural optimisation is a mathematical approach towards reducing the amount of material and consequently cost, also simultaneously, sustaining the applied load and architects' aesthetic requirements (Belegundu & Chandrupatla, 2011). In the simplest case, optimisation includes maximising or minimising an objective function (Delgarm, Sajadi, Delgarm, & Kowsary, 2016). A general structural optimisation problem can be defined as following: (Christensen & Klarbring, 2009)

$$\begin{cases} minimises/maximises\ f(x,y)\ with\ respect\ to\ x\ and\ y \\ \qquad subject\ to\text{:} \begin{cases} behavioral\ constraints\ on\ y \\ design\ constraints\ on\ x \\ equilibrium\ constraints \end{cases} \end{cases}$$

Where:

- $f(x,y)$: $Objective\ function$, is used to classify the design and aims to either minimise or maximise the value. According to the aim of designer, this value varies; it can measure cost, weight, displacement, stress etc. In this process, different design variables can be used to generate different design options with various objective functions. In the optimisation process, the objective function represents the value of the alternatives in each generation (Jin & Jeong, 2014).

- x: $Design\ variable$, represents the geometric properties of design and it can be altered during the optimisation process. The proposed prototype uses different x variables as design variables to use in the predefined functions and generate different structural models.
- y: $State\ variable$, is a function that defines (generates) the result of the structure for the specific x value.

Structural optimisation can be classified into three optimisation methods including shape optimisation, topology optimisation and size optimisation (Bendsøe & Sigmund, 2003; Christensen & Klarbring, 2009; Haslinger & Mäkinen, 2015). Table 3 shows similar work on the optimisation of the structural design. This table highlights the optimisation methods, which have been used in each research and explains the limits of the research, which is covered in this thesis.

Reference	Title	Optimisation method	Limitations
Dapogny et al. (2017)	Geometric constraints for shape and topology optimization in architectural design	Shape and topology optimisation	Limited to the conceptual architectural design
Stromberg et al. (2011)	Application of layout and topology optimization using pattern gradation for the conceptual design of buildings	Topology optimisation	Limited to the structural analysis without linking to the architectural model
Stromberg et al. (2012)	Topology optimization for braced frames: Combining continuum and beam/column elements	Topology optimisation	Limited to 2D braced frame and structural analysis without linking to the architectural model
Beghini et al., (2014)	Connecting architecture and engineering through structural topology	Topology optimisation	Limited to the integration process without structural analysis

	Optimization		
Allaire et al. (2014)	Shape optimisation with a level set based mesh evolution method	Shape optimisation	Limited to the structural analysis without linking to the architectural model
Allahdadian et al. (2012)	Towards optimal design of bracing system of multi-story structures under harmonic base excitation through a topology optimization scheme	Topology optimisation	Limited to harmonic structural analysis without link with the architectural model
Tomás and Martí, (2010)	Shape and size optimisation of concrete shells	Shape and size	Limited to shape and size optimisation without considering topology optimisation.*
Bogomolny and Amir (2012)	Conceptual design of reinforced concrete structures using topology optimization with elastoplastic material modeling	Topology optimization	Limited to the design optimisation of RC structure.
Besserud et al. (2013)	Structural Emergence: Architectural and Structural Design Collaboration at SOM	Shape and topology optimisation	This research uses FEA to show the effect of loads and stress distribution and helps the architects to design based on the engineering preferences.
Blasques & Stolpe (2012)	Multi-material topology optimization of laminated composite beam cross sections	Topology optimisation	Limited to the laminated composite beam cross section
Tsavdaridis, (2015)	Applications of Topology Optimization in Structural Engineering : High-Rise Buildings and Steel Components	Topology optimisation	Lack of support the current common structural design and architectural process to indicate the location of the structural elements.
Kazakis et al. (2017)	Topology optimization aided structural design: Interpretation, computational aspects and 3D printing	Topology optimisation	Lack of support the current common structural design and architectural process to indicate the location of the structural elements.
Granadeiro et al.(2013)	Building envelope shape design in early stages of the design process: Integrating	Shape optimisation	Limited to the envelope shape optimisation and energy simulation.

	architectural design systems and energy simulation		
Eleftheriadis et al. (2015)	BIM Enabled Optimisation Framework for Environmentally Responsible and Structurally Efficient Design Systems	Size optimisation	No integration with the architectural model

Table 3: overview of the extant research on different structural optimisation methods and limitation of the researches, which are covered to some extent in this research.

The following are the solutions proposed in this research to solve the limitations found in the reviewed researches and articles:

- Flexibility to be used in different stages of structural design from the conceptual design stage to the detail design stage, although this research focuses on the conceptual stage.
- Capability of solving various design problems based on the need of the designer and the type of the structure such as deflection, stress, bending moment etc.
- Automatic integration with the architectural model.

2.1.2.1 Shape design and optimisation

The envelope shape of a structure separates it from the surrounding environment and its shape has significant effect on different areas such as cost, safety and strength, energy performance etc. (Ding, Seifi, Dong, & Xie, 2017; Su et al., 2019). Therefore, envelope shape design is considered as the most salient feature in design (Vasco Granadeiro, Duarte, Correia, & Leal, 2013). Envelope shape is often defined during the early design stages and includes very limited rule of thumb structural engineering judgments. Shape optimisation is often performed during architectural design in building designs or during the structural designs in which structural engineer can contribute to the envelope shape of the structure. For instance, building shape is a vital factor during the design of high rise towers in which the shape of the building has a significant effect on the behaviour of the structure against wind load (Beghini et al., 2014; Stromberg et al., 2012).

2.1.2.2 Topology optimisation

Michell (1904) proposed the first solution to a topology optimisation problem in the form of a simple loading and boundary condition of a truss structure. Afterward, numerous techniques for the solution of structural topology optimisation have been suggested such as the evolutionary procedure (von Buelow, Falk, & Turrin, 2011), the bubble method (Eschenauer, Kobelev, & Schumacher, 1994), the level set method (M. Y. Wang, Wang, & Guo, 2003) and the topological derivative method (Norato, Bendsøe, Haber, & Tortorelli, 2007). Structural topology optimisation helps the designers to determine information on the optimum amount of material or number of structural elements (Tsavdaridis et al., 2015). Jewett and Carstensen (2019) believe that topology optimisation helps to leverage the new manufacturing possibilities. They argued that this method is a freeform engineering design that enables the designer to automatically create efficient designs within a design domain by ascribing the material (elements) to key locations of a structure (Jewett & Carstensen, 2019). Furthermore, Beghini et al. (2014) argued the potential of the topology optimisation in connecting the architecture and engineering disciplines. This has made topology optimization a popular design tool for a wide range of applications, but the examples related to civil structures and components remain limited. According to Chan and Wong (2008) the potential savings from topology optimisation are generally more significant than those resulting from element sizing optimisation alone.

2.1.2.3 Size or cross section optimisation

Current structural design processes often separate the design of a building framework into two steps:

1. Defining the structural form (topology) of the building
2. Deciding the size of the elements

However, the behaviour of the structural elements is highly related to the property of the structural elements. Therefore, the structural efficiency of a building framework varies with changing element sizes. Therefore, the optimisation process requires a simultaneous topology and elements sizing design optimisation (Chan & Wong, 2008). Although, most published papers deal with size optimisation where the shape of the structure and locations of the members (topology) are fixed (Aldwaik & Adeli, 2016). However, this research proposed a new framework, which enables the designer to perform all three types of the optimisation simultaneously.

2.1.3Multi-disciplinary Design Optimization (MDO)

The building design process is a creative and complex process, which includes multiple conflicting criteria (Díaz et al., 2017). When conflicting goals are required to be achieved simultaneously, a single objective function is not sufficient to define the problem and multi-objective optimisations arise (Delgarm et al., 2016). In addition, traditional methods of design optimisations require tedious and time-consuming manual iterations (W. Wang, Rivard, & Zmeureanu, 2005). Multidisciplinary Design and Optimisation (MDO) has emerged in the AEC industry to assist designers in generating more design alternatives in less time (Díaz et al., 2017). MDO is an optimisation method for design of complex systems. This method attempts to breakdown the problem into smaller sub-problems and explore the iteration of various disciplines (Ren, Yang, Bouchlaghem, & Anumba, 2011). Researchers in the aerospace (J.-H. Zhu et al., 2016) and automotive industries (C. J. Chen & Usman, 2004) have developed methods for MDO to design and analyse design alternatives during the conceptual stage of a project. However, application of MDO to AEC industry has been comparatively modest (F. Flager & Haymaker, 2009). AEC professionals often design and analyse very few design alternatives during the conceptual stage of a project due to the limitations in the processes and the software tools used by the AEC industry (W. Flager et al., 2009). Rahmani Asl, Stoupine, Zarrinmehr, and Yan (2015) argued that there is a lack of MDO tools to access the rich data stored in BIM to assist designers in exploring design alternatives across multiple competing design criteria. Application of MDO methods has shown significant improvements in building performances compared to the traditional design process (Rahmani Asl, Stoupine, et al., 2015). One of the widely used platforms for MDO is BIM and parametric modelling and analysis tools such as structural analysis, energy simulation, and cost analysis and so on (Asl, Stoupine, Zarrinmehr, & Yan, 2015). Díaz et al. (2017) conducted a literature review on the recent MDO research in the AEC industry, which summarises different disciplines involved in the optimisation studies (figure 6). According to this figure, energy (34%) and cost (21%) has the highest number of research investigations in MDO scope, which is followed by architecture (15%) and structure (13%). According to this figure, despite the lack of application of MDO in AEC, there is a great lack of attention to the use of MDO in structural design processes.

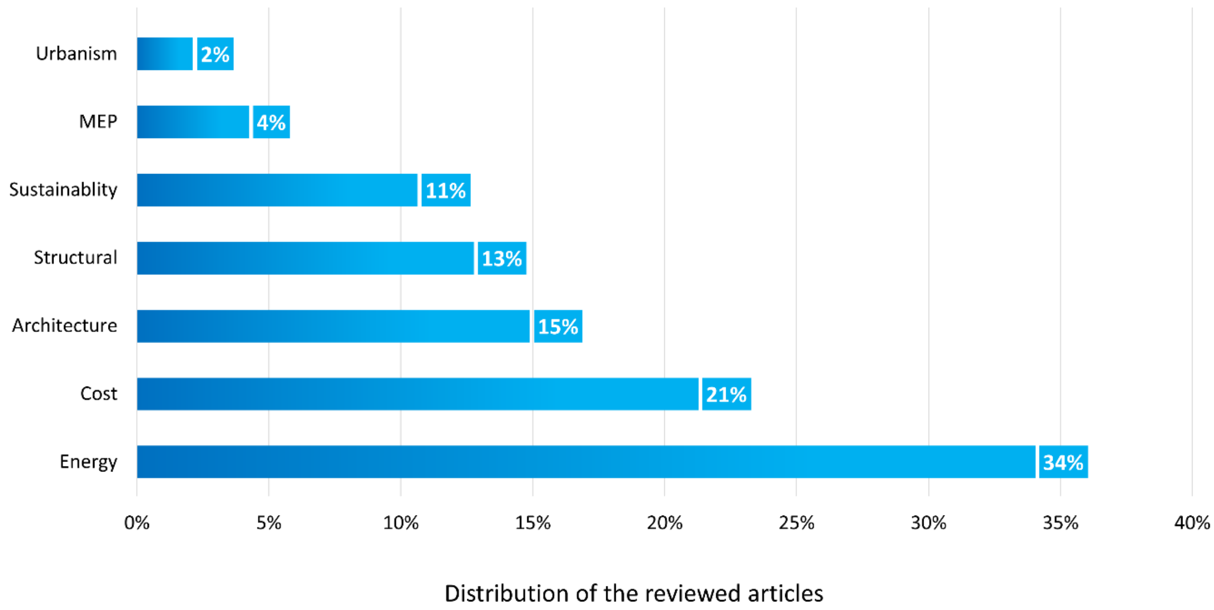


Figure 6: Extant literature on the Multidisciplinary Design and Optimisation (MDO) research in the AEC industry (Díaz et al., 2017).

2.1.4The iterative structural design process

Even though BIM technology to some extent facilitated the integration between different disciplines, there are still issues during the iterative design process in AEC industry (Allaire et al., 2014; V. Granadeiro et al., 2013b). The design process in the AEC industry is complex in nature and includes much iterative work and design quality changes (Nour & Beucke, 2019). Current structural design and construction process are becoming increasingly complex because of the introduction of new building technologies, research and stringent building regulations (N. O. Nawari, 2011). In this complex process, it is the structural engineers' responsibility to evaluate the buildings' strength against gravity and lateral forces. They are constantly struggling with checking the conformance of the generated models to various national and international codes (N. Nawari & Kuenstle, 2015). These challenges highlight the need to a profound collaboration between project stakeholders and an intensive verification of the building design starting in the conceptual stages (N. O. Nawari, 2011). This research uses an automated structural analysis system that evaluates the building design according to various structural design and analysis regulations. This includes evaluating and reviewing the functional capabilities of the generated structural models and facilitating the optimisation process and decision-making.

Furthermore, structural design is a multidisciplinary process that can be performed in different ways including sequentially, concurrently or in parallel (Nour & Beucke, 2019). Therefore, the design needs to pass through several versions to generate different alternative solutions during the entire design process and to meet the criteria of each stage (architectural, structural etc.). In this process, design changes are inevitable due to the iterative and exploratory nature of design (Gheisari & Esmaeili, 2019). Design changes are common and likely to occur in different disciplines for different reasons at any time, which can create major delays and disruption, and it is highly accepted by both owners and constructors that change effects are difficult to quantify and frequently lead to clashes (Motawa, Anumba, Lee, & Peña-Mora, 2007). Therefore, detection of design changes is essential for collaboration in the design process of buildings (Lin, Zhou, Zhang, & Hu, 2019). More often, various design solutions are produced as alternative solutions or different development stages that need to be compared with the original design aims and their conformance to the client and other disciplines requirements be evaluated (Nour & Beucke, 2019). Woodbury and Burrow (2006) believe evaluation and comparison are the main benefits of the exploration of various design alternatives. On one hand, alternative design provides solutions, which the designers may have never considered (C. Lee & Ham, 2018). Therefore, these alternatives suggest innovation and future avenues of exploration. On the other hand, comparison between different alternative design solutions plays a key role in selecting the best design among different alternatives (J. P. Basbagill et al., 2014).

This research proposed a new framework that facilitates the iterative process of structural design and design change detection. This framework uses automation to update the structural models based on changes in the architectural model. This framework has many advantages for the building process including; reducing the time of iterative design process by using automatic synergy between architects and engineers. Moreover, this framework uses parametric data of the architectural model from Revit, such as location of the elements, to maximise the synergy between two disciplines. This automatic synergy of the parametric data increases the accuracy of the design process and conformance between architectural and structural models. Furthermore, this scenario is applied to all the alternative structural models, which are designed for the same architectural model. This system enables the designers to evaluate and compare various structural design alternatives and facilitates the collaboration and data exchange between architects and structural engineers in generating volume and structural system. Therefore, this system produces economical and high-performance conceptual structural solutions with less time and effort and with a high accuracy, conformity and quality. Furthermore, the generated alternative solutions respect the space and aesthetic requirements of the architectural models.

2.2 Building Information Modelling (BIM)

The term "Building Information Modelling" for the first time appeared in an article published in an automation and construction journal (van Nederveen & Tolman, 1992). However, the first use of term BIM was in an article by Hoekstra (2003). Van Nederveen and Tolman argued that BIM is a new method to model building information according to multiple aspects such as spatial design, building structure, and energy (Santos, Costa, & Grilo, 2017). Since then, the research on BIM has been growing significantly and new applications were explored such as a data driven concept focused on coordinating information exchanges (NCS, 2019). The current concept of BIM refers to the combination of a set of technologies related to the generation of a 3D model and with the handling of a large amount of data (Sampaio & Berdeja, 2017). BIM technology has been rapidly recognized to change the process of how construction projects are delivered (Zhang et al., 2015). The construction industry indicates evidence of the potential of BIM to transform the design methods and construction (L. Chen & Luo, 2014). Currently, BIM is one of the most promising recent developments in the AEC industry (Azhar, 2011) which has transcended all disciplines (Issa & Olbina, 2015). The ability to design and analyse buildings and infrastructures, integrate schedule and cost data with the analysis and design process in BIM has made it a very popular system in the AEC industry (Issa & Olbina, 2015). It enables the AEC specialists to visualise the future building in a virtual environment by object-based modeling (J. C. P. Cheng, Lu, & Deng, 2016), plan the forthcoming construction processes, and identify any potential design, construction, or operational issues (Vilutiene et al., 2019). The standardisation of the BIM data is known as an important part of the innovation (van Berlo, 2019). These benefits have significantly changed the traditional CAD solutions and improved the project delivery process (J. C. P.

Cheng et al., 2016) and helps to make BIM technology one of the promising methods for automation (Pučko, Šuman, & Rebolj, 2018). Civil engineers in general and structural engineers in particular can benefit from these technologies (Bartley, 2017; Hosseini, Maghrebi, Akbarnezhad, Martek, & Arashpour, 2018). For instance, BIM has improved the traditional way of presenting design objectives by adding an intelligent system , which includes detailed information and involving human interpretation on the drawing (J. C. P. Cheng et al., 2016).

2.2.1Application of BIM

The application of BIM in the building design and the construction industry is growing rapidly (Zhang et al., 2015). Many researchers have evaluated the benefits of BIM within different educational or industrial settings (Barlish & Sullivan, 2012; C. Chen, Dib, & Lasker, 2011; Peterson, Hartmann, Fruchter, & Fischer, 2011; Sacks, Koskela, Dave, & Owen, 2010; Solnosky, 2013). Azhar (2011) stated that the construction industry is capable of using BIM in different areas such as visualisation, fabrication, code review, cost estimating, construction sequencing, conflict, interference, and collision detection; and forensic analysis and facility management. Many research investigations proved the advantage of BIM in various fields such as reducing design clashes, increasing productivity, improving flexibility in design, reducing design time and cost, improving collaboration between different construction stakeholders, etc. (H.-L. Chi et al., 2015). Therefore, in 2011, the UK Government, which is the largest client of the construction industry, mandated the use of BIM level 2 in all the public sector centrally procured construction projects by 2016 (Cabinet Office, 2016; GOV.UK, 2011; “Standards | BIM Level 2,” 2016). The purpose of this decision was to reduce 33% in costs, 50% in CO2 emissions, and 50% in overall project delivery times during period of 2011-2016 (Cabinet Office, 2016). Successful BIM implementation on buildings has reaped the rewards of lower cost and higher productivity, accuracy, communication and efficiency in the building market (J. C. P. Cheng et al., 2016). Existing literature indicates an increasing growth in the use of BIM in AEC industry particularly after 2012 (Figure 7) (Akintola, Senthilkumar Venkatachalam, & Root, 2017; Hosseini et al., 2018; Santos et al., 2017; Vilutiene et al., 2019; Yalcinkaya & Singh, 2014). This growth can be associated with the decision of the Government Construction Strategy of the United Kingdom in 2011 to mandate the use of BIM Level 2 on all public sector projects by 2016 (GOV.UK, 2011).

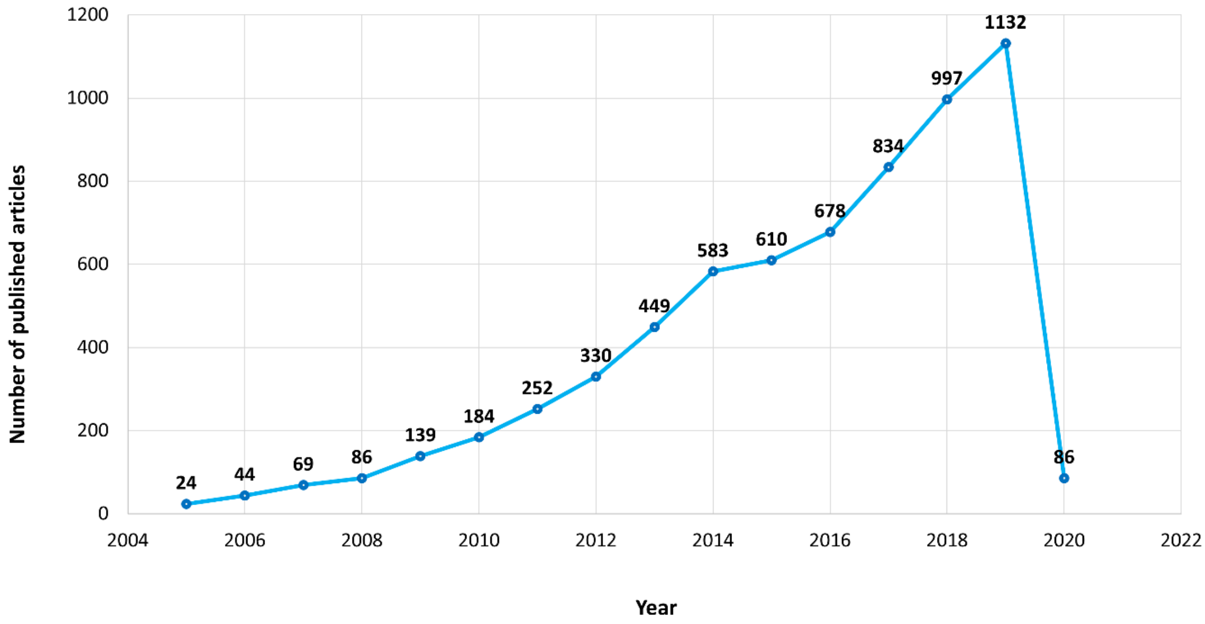


Figure 7: Increasing research in BIM from 2005 until February 2020. The sharp decline of the graph is associated with the timing of the research.

Hosseini et al. (2018) and (Santos et al., 2017) performed systematic analysis on the variation of the total number of BIM related publications during 2003-2017 and 2005-2015 respectively. The bibliometric analysis indicates that research in the BIM area is dominated by generic tasks of BIM such as information management; while limited research focused on the technical issues of structural engineering (Hosseini et al., 2018; Santos et al., 2017). Furthermore, the comparative analysis of BIM in the AEC industry indicates the use of BIM enhanced the traditional project management and transformation of project delivery method (Shou, Wang, Wang, & Chong, 2015). In a research conducted by Vilutiene et al. (2019) demonstrated the recent development and implementation of

BIM in the structural engineering by using three dimensional, collaborative and parametric design tools. Furthermore, literature review demonstrates new researches on automation, decision making, and optimisation (Olawumi & Chan, 2018). Selçuk Çldlk, Boyd and Thurairajah (2017) believe that BIM users adopt a certain view of BIM depending on their job and perspective but are not aware about its innovative capability. Furthermore, they argued that innovation has been elusive because of the inherent social and organisational complexity of construction. However, with the increasing amount of BIM adoption in the construction industry, Chi et al. (2015) expected an increase in the BIM-enabled structural design to shift the structural design by using cutting edge technology. Furthermore, the success of BIM implementation in industrial projects and the success of BIM case studies in academic journals inspired BIM research and development in academic area (Hosseini et al., 2018; Shou et al., 2015; Vilutiene et al., 2019). Vilutiene et al. (2019) performed bibliometric analysis on 369 papers to create a wide overview of published papers that relate to the structural engineering in BIM platform. The results of the bibliometric analysis indicated that the research in BIM structural engineering has increasing popularity particularly after 2012 (Vilutiene et al., 2019). However, the amount of research on structural engineering and BIM is significantly less than the research on BIM in general. Comparison between the results of the bibliometric analysis proposed by Vilutiene et al. (2019) (figure 8) with the research on BIM (figure 7) indicates that almost 7% of research on BIM referred to structural engineering applications. This highlights the fact that there is a significant lack of attention to the structural engineering in BIM technology in the existing research and literature (Shou et al., 2015). Previous researches highlight a similar delay in application of BIM in various areas followed by a gradual growth (He et al., 2017) and success in industrial application (Shou et al., 2015). BIM has considerable potential to address complex problems in specialised areas of structural engineering. Therefore, Vilutiene et al. (2019) believes the delay in research on the application of BIM in structural engineering reveals a great potential for implementing BIM.

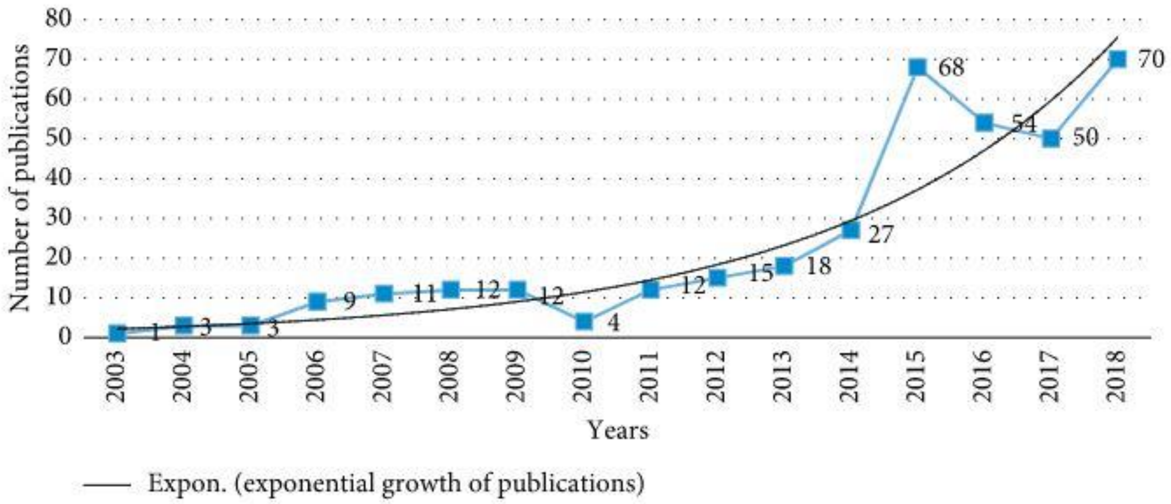


Figure 8 Variations in the number of BIM publications in the area of structural engineering (Vilutiene et al., 2019).

2.2.2BIM-enabled structural engineering

Structural design and analysis is one of the most required uses of BIM technology (Y. Jung & Joo, 2011). Converting an architectural building information model to an engineering analytical model requires a considerable amount of time and effort. Moreover, extensive amendments are needed to make the structural model ready for analysis (Ramaji & Memari, 2018).

2.2.2.1 Design and interoperability

The main concept of BIM models are 3D geometric which are encoded, in various proprietary formats with the capability to adopt time/schedule (4D) and cost (5D) attached to them (Bilal et al., 2016). This concept provides object-oriented digital information of the design by using data-rich models and facilitates the simulation for design and analysis process (Sacks, Eastman, Lee, & Teicholz, 2018). Many vendors argued that BIM tools are capable of supporting three main tasks for structural engineering: geometry design, material property and loading conditions for analysis (Vilutiene et al., 2019). All the required information can be directly obtained from a BIM model such as Autodesk Revit, edited and sent for structural design and analysis in other BIM software such as Robot Structural Analysis (Sacks et al., 2018). Moreover, the use of BIM for structural design can be coupled with other disciplines such as the fabrication and assembly of structural elements and identifying the coordination issues (Okakpu et al., 2018). This coordination and advanced visualisation can help to reduce the number of requests for information items from contactor, clients and stakeholders (Papadonikolaki, Vrijhoef, & Wamelink, 2016). Furthermore, the BIM platform dynamically links design and construction data which considerably reduces the required time to evaluate more alternative solutions, execute design changes and generate construction documentations (Ahn, Kim, Park, Kim, & Lee, 2014; Strafaci, 2008). In this process, structural engineers can keep the model constantly updated with any change in the design and produce a highly accurate (Hunt, 2013). Yet, interoperability issues still exist between different BIM technologies (Bynum, Issa, & Olbina, 2013). McGraw Hill stated that 8 in 10 users of BIM technologies in the US struggle with the interoperability (Z.-Z. Hu, Zhang, Wang, & Kassem, 2016). Muller et al. (2017) stated that efficient use of BIM models for engineering purposes requires a high level of interoperability among different design and analysis tools. Chi et al. (2015) argued that systematic modelling and interfaces for data exchange are the future of the structural design process. There is considerable research on the interoperability between architectural design and structural design and analysis. For instance P.-H. Chen et al. (2005) adopted Industry Foundation Class-based (IFC-based) information to enhance an effective collaboration between architects and structural engineers. Liu and Zhang (2010) developed an algorithm to automatically generate a structural model from the IFC-based architectural model. Hu and Zhang (2011) proposed an integration tool to achieve a BIM-based dynamic environment for conversion between structural information models. Currently, BIM is getting more online and in cloud servers by using technical standardised interfaces (APIs) which provides the opportunity to innovate the industry with BIM services for automatic collaboration (van Berlo, 2019). Many researchers believe that BIM is capable of being an effective part of structural design optimisation (Asl et al., 2015; Díaz et al., 2017).

2.2.2.2 Analysis and optimisation

In complex construction projects, several structural analysis methods are adopted to verify the structural safety and compliance of the proposed design (Z.-Z. Hu et al., 2016). Structural BIM is the most efficient method for the structural engineers and their immediate supply chain (Robinson, 2007). CIC research group argued that BIM engineering analysis tools enable the users to perform more efficiently by using intelligent methods, design specifications and building information model (Kreider & Messner, 2013). BIM supports structural analysis procedure in various areas such as buildings (Vitiello et al., 2019), bridge design (McGuire, Atadero, Clevenger, & Ozbek, 2016), and tall buildings (Robinson, 2007). BIM technology facilitates the engineering analysis process automatically and saves a considerable amount of time and cost for users (Alwisy, Al-Hussein, & Al-Jibouri, 2012). BIM-based engineering analysis, including structural analyses, and sustainability evaluation can be performed automatically and save time and cost, and improve the design quality (Won & Cheng, 2017). Furthermore, BIM technology is capable of facilitating the optimisation process by quickly resolving design and constructability issues in the early phases of AEC projects (Anumba et al., 2010). The required information about the quantity of construction materials for each alternative solution can be quickly and automatically extracted from BIM models (Won & Cheng, 2017). Existing literature demonstrated that the important areas for future research include automation of the assembly sequence, modelling of structural components, planning and optimization of off-site construction, and dynamic structural health monitoring (Vilutiene et al., 2019). Therefore, BIM is a potential platform for the future research in automation and optimisation.

2.2.3Digitalisation

The transaction from two-dimensional (2D) to three-dimensional (3D) computer modelling of building structures has a great effect on the structural engineering design process in many ways such as: conceptual design, structural analysis, layout, detailing and fabrication (Sacks & Barak, 2008). In recent years, the main focus of the computer aided tools development was on the quality of the finished project, flexibility of design modification and error detection (H.-L. Chi et al., 2015). For structural engineers, the invention of Finite Element Methods (FEM) had a significant contribution to the analysis and optimisation process (Guo & Cheng, 2010). In this scenario, the increasing demand on the structural design efficiency and reliability have made structural optimisation and automation a popular research area (H.-L. Chi et al., 2015; Hosseini et al., 2018). Despite a considerable progress in technology, computer support for conceptual structural design is still ineffective. This is due, in part, to the fact that current computer tools do not consider structural design and architectural design as interdependent processes, particularly at the early stages (Mora, Bédard, & Rivard, 2008). They lack unified data sources to apply to both architects and engineers. Chi et al. (2015) argued that the existing modelling tools at the conceptual or detail stages fail to provide various design solutions from architectural and structural aspects. This lack of performance limits the space to explore superior design solutions at the early stages. Furthermore, current structural design tools lack in supporting optimisation and interactive modelling especially at the early stages for conceptual design, simply because the focus of the numerical methods are on later detail design stages (Gerold, Beucke, Seible, & Asce, 2012). Although these tools are capable of providing valuable feedback about important aspects of structural performance, like robustness, redundancy, and ductility (Gerold, 2019). Therefore, structural engineers still rely on their knowledge, skills and experiences to make decisions between different alternative conceptual designs (H.-L. Chi et al., 2015). Existing literature indicates an increasing amount of research in the early stages in which, BIM technology plays a critical role and has already indicated great benefits to the construction industry (Hosseini et al., 2018).

2.2.4Parametrised modelling

Architectural and structural design projects are growing rapidly and the complexity of these projects requires more effort during the numerous design steps of the modelling process (Kazakis et al., 2017). Even with the advantage of computer-aided design, designers still suffer from conflicts and inconsistency problems (H.-L. Chi et al., 2015). Therefore, many practitioners and researchers from various design areas believe that concurrency of knowledge and interdisciplinary collaboration during the design process are critical factors to provide better solutions (Cavieres et al., 2011; Shen, Hao, & Li, 2008) . Hence, numerous researchers focused on developing computer applications to support integration during the entire product development process. In this process, Information Technology (IT) had a great contribution to the growing technology of Building Information Modelling (BIM) to develop the next generation of the Computer-Aided Design (CAD) for buildings from the conventional CADD (Computer-Aided Drawing and Design) (G. Lee, Sacks, & Eastman, 2006).

Barrios (2005) described parametric design as the process of designing with parametric models and information or in a parametric modelling setting. This process enables the designers to change the shape of model geometry as soon as the dimension value is modified to support the revelation and comparison performances (Turrin et al., 2011). This process is implemented through the design computer programming code such as a script to define the dimension and the shape of the model. The model can be visualized in a 3D view to resemble the features of the real model (Fu, 2018). Parametric design is the most striking feature of BIM which presents all the building information in the form of components (Yuan, Sun, & Wang, 2018). Architectural and structural modelling processes are becoming more flexible due to the progress in parametric design which facilitates geometrical modelling, clash detection, decision making and increases the quality of the project (H.-L. Chi et al., 2015). Parametric modelling for buildings provides intelligent building objects such as walls, windows and furniture for architects; columns, beam and bracings for structural engineers and mechanical objects such as bolts, nuts and pipes and valves for mechanical engineers. Functional intelligence varies these objects to be distinguished in terms of behaviour and functionality. For instance, in terms of architectural design, doors and windows can be located in the walls automatically. In addition, in structural design reinforcement that must be located in the concrete can be performed automatically (G. Lee et al., 2006). Parametric modelling provides mechanisms to translate and embed domain expertise as an accurate geometric model that is capable of automating the generation of the building information particularly geometric information and design (G. Lee et al., 2006). This method provides a great help in facilitating the design process and generating a rich building model (Shen et al., 2008). There are numerous research investigations focused on customising the existing CAD systems to automate the routines through an Application Programming Interface (API) and generate add-ons, plug-ins, and macros. However, many of the developed tools focus on the late design development activities, such as detail engineering analysis or simulation and optimisation (Cavieres et al., 2011), but relatively there is very limited application of the conceptual design stages (L. Wang et al., 2002).

2.3 Artificial Intelligence (AI)

The AEC industry is fraught with complex and difficult problems (Darko et al., 2020). According to the recognised challenges of exploring alternative solutions of a model, many research investigations argued that the combination of parametric modelling with other computational methods including search methods related to the analysis and evaluation of the performance value is an efficient method to explore better performing solutions (Turrin et al., 2011). Artificial Intelligence (AI) represents a powerful method to mimic intelligent human behaviour, thus seeking to use human-inspired algorithms for approximating conventional problems (Salehi & Burgueño, 2018) by using intelligent systems and technology to integrate physical and virtual (digital) worlds (Darko et al., 2020). Furthermore, AI has a significant influence on the productivity improvements by analysing a large amount of data quickly and accurately (Patrício & Rieder, 2018). This technology is proving to be an efficient alternative method to classic modelling techniques (Salehi & Burgueño, 2018).

In the traditional methods of design, once the design is generated any change in the design parameters, requires the entire process to be repeated. In this process the idea of change, edit and develop is time consuming and this could iterate until a feasible solution is achieved. In contrast, parametric design enables the designer to adopt certain tools such as Dynamo or Grasshopper to efficiently change and improve the design by integrating and coordinating design components simultaneously (Eltaweel & SU, 2017). Therefore, any change in the design parameters will be automatically and immediately updated in the model. Hence, the use of AI is significantly increasing within a wide range of industries (Mellit & Kalogirou, 2008). Darko et al., (2020) conducted a comprehensive bibliometric analysis on 41,827 relevant publications to demonstrate the trend of research on AI in the AEC industry from 1974 until august 2019 (Figure 9). According to this figure, there are many more publications available in the 21st century compared to the 20th century. This reveals the importance of AI research fields in the 21st century (Oke, 2008). This increasing interest in AI in AEC industry is in line with the argument by Bilal et al. (2016) that the AEC industry deals with large amounts of heterogeneous data to extract useful insights for better decisions and state of the art development on the task. According to Darko et al. (2020) the main focus of the AI research in AEC industry is on the optimisation process by using Genetic Algorithms (GA). This shows that GA is the most common AI method for optimisation process in AEC industry (El-Abbasy, Elazouni, & Zayed, 2016; K. Kim, Walewski, & Cho, 2016; J. Lee & Hyun, 2019).

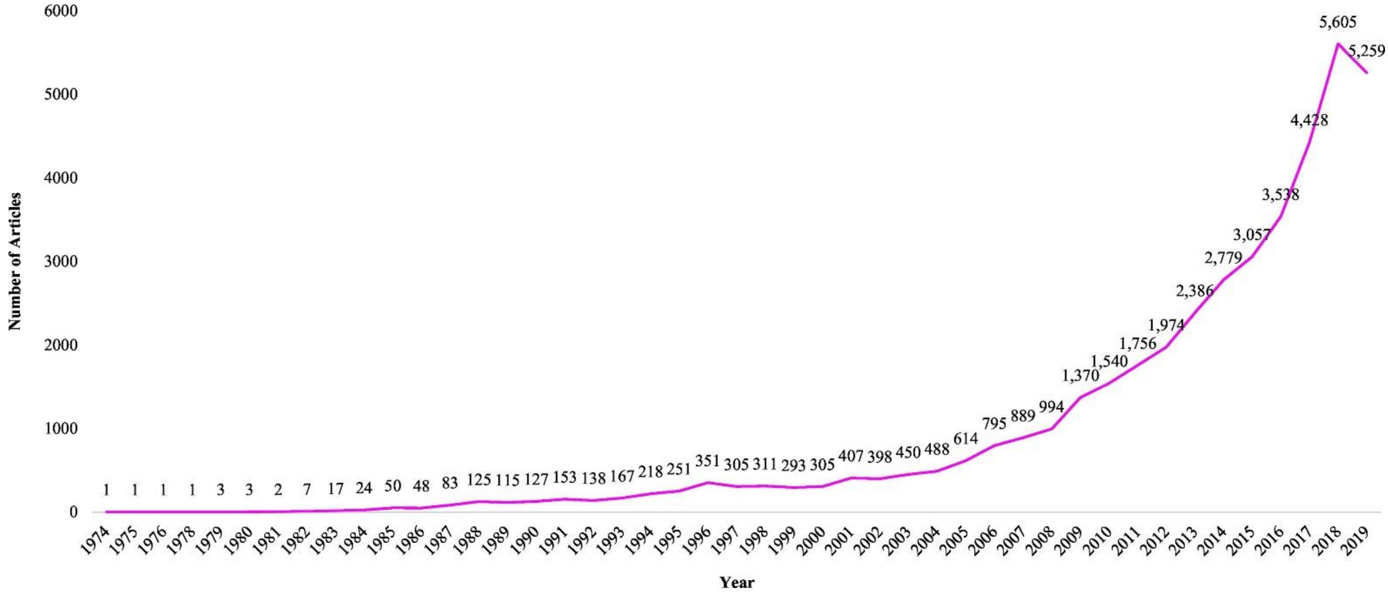


Figure 9: Trend in research publications on the AI in the AEC industry (1974–Aug2019 (Darko et al., 2020)

Powered by AI and the computing technology Autodesk (2018) generative design technology enabled the designers to simultaneously produce alternative designs according to the manufacturing and product performance requirements. This technology enables the designers to evaluate, filter and select the optimum solution between the alternatives. With the ability to explore numerous alternative valid solutions, designers are no longer limited by personal imaginations and experiences. Automated modelling has a considerable progress in the recent research in various areas such as:

- Modelling of fabricated construction components (Sharif, Nahangi, Haas, & West, 2017)
- Construction progress monitoring (Pučko et al., 2018)
- Status assessment and quality assessment
- Automated planning of concrete joint layouts with 4D-BIM (Sheikhkhoshkar, Pour Rahimian, Kaveh, Hosseini, & Edwards, 2019)
- Automatic light-frame roof construction (H. Liu, Sydora, Altaf, Han, & Al-Hussein, 2019)
- BIM-based automated design and planning for boarding of light-frame residential buildings (Hexu Liu, Singh, Lu, Bouferguene, & Al-Hussein, 2018)

- Automated systems for the continuous monitoring (Sun, Staszewski, & Swamy, 2010).

However, automatic structural design and engineering still lacks in different areas such as Automated three-dimensional (3D) modelling (J. Jung, Hong, Yoon, Kim, & Heo, 2016), structural elements detection and structural optimisation (Rian & Sassone, 2014), automation of the assembly sequence and Planning off-site construction (Arashpour et al., 2019; Y. Wang, Yuan, & Sun, 2018). This lack of research calls for more investigation in these areas.

2.3.1Generative Design (GD)

The generation and exploration of design space is an iterative and time-consuming process and the system has to generate and compare a variation of models for specific or multi requirement (Nordin et al., 2013). In this process, designers and engineers would take the client requirements and try to produce alternative design concepts and evaluate them until they find one that meets the requirements (Autodesk, 2018). This highlights the need to have a system to explore the space for the potential feasible solutions because there is not enough time to explore all the possible valid solutions manually.

Generative design is a design exploration process, which helps to generate high-performing design alternatives in considerably less time than the conventional manual process. As algorithms and scripting become more accessible to designers; parametric tools, simulation software, optimisation and generative algorithms are dominating generative design methods (Agkathidis, 2015). In this process, the software uses design goals along with performance parameters or special requirements, materials, costs and strength to quickly explore all the possible solutions (Autodesk, 2020). Bohnacker et al. (2009) described Generative Design (DG) as a loop process based on an initial idea, which is applied to a rule or algorithm (figure 10).

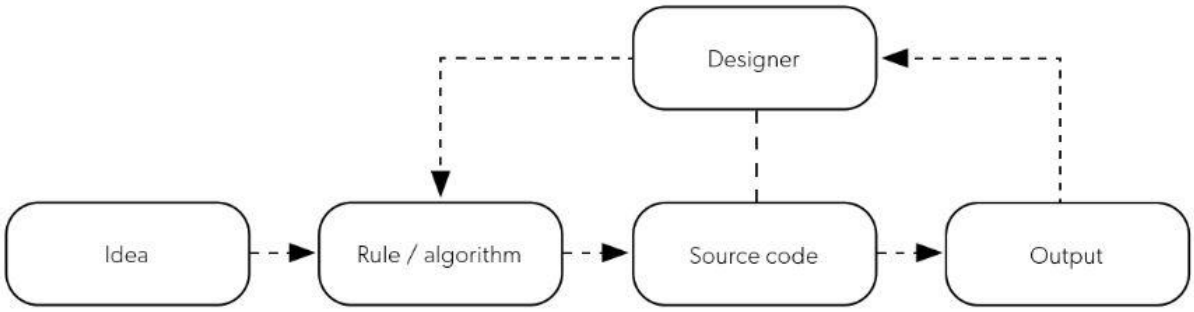


Figure 10: generative design process diagram by (Bohnacker et al., 2009).

The importance of exploring different design alternatives is known as a great feature of the conceptual design stage (Y.-C. Liu, Chakrabarti, & Bligh, 2003). Generative design technology has considerable benefits for the design exploration and production process. The primary benefits are:

- Reducing the amount of time to design a product
- Providing the designer with design options which the designer might have never considered

Recently, the increasing complexity of structural engineering applications has revealed the need for automation (Mobasher, Rashed, & Elhaddad, 2016; Venugopal, Eastman, Sacks, & Teizer, 2012). Progress in GD can significantly improve the design process, particularly for resource optimisation and waste reduction (Bilal et al., 2016). These technologies can undoubtedly bring new levels of usability, accessibility, and democratisation in the design exploration and optimisation (Bilal et al., 2016). Therefore, there are many underlying challenges to be met before GD is realistically achieved. The first concern in the generative design of alternative solutions and their performance evaluations with search algorithms is to find the satisfying parametric configurations among the entire collection of instances of the parametric model (Turrin et al., 2011). However, it might be practical for relatively small number to use all the design variables (parameters) to generate alternative designs. This method would become impractical when the number of independent design variables (parameters) increases due to the time consuming computational effort of a systematic generation and performance evaluation. Therefore, in the automatic generative design process, the selection of independent design variables (parameters) plays a critical role for the efficiency of the method (Turrin et al., 2011). Optimisation algorithms, which control the generation of parametric design alternatives, facilitate the cumbersome computation process by using stochastic methods (Turrin et al., 2011). This method helps designers in creative design space exploration and supports decision making by ranking design alternatives according to multiple design criteria (Rahmani Asl, Stoupine, et al., 2015). In this process, the computer is responsible for certain tasks including generate a population of solutions, allow the fittest/ most suitable solution to regenerate and exclude the less fit / suitable solutions (Renner & Ekárt, 2003). There is an increasing interest in integrating generative design for optimisation in engineering design and decision making for effective exploration of the solution space (Mourshed, Shikder, & Price, 2011) (see table 4).

Reference	**Area**	**Stage**	**Method**
(S. Banihashemi, Tabadkani, & Hosseini, 2018)	Construction waste reduction workflow	NA	Grasshopper
(Eltaweel & SU, 2017)	Energy	Early stage	Grasshopper
(Turrin et al., 2011)	Architectural design	Early stage	GA
(Tuhus-Dubrow & Krarti, 2010)	Architectural design- building shape and building envelope features	NA	GA

Table 4: Extant research on using generative design

2.3.1.1 Genetic Algorithms (GA) combined with parametric modelling

Genetic algorithms (GA) are biologically inspired and represent a new computational model having its roots in evolutionary sciences (Meyer-Baese & Schmid, 2014). Holland (1992) for the first time coined the idea of Genetic algorithms optimisation (Yang, 2013). New generations in GA use the Darwinian principle of reproduction and survival of the fittest of natural occurring genetic operations (Chalabee, 2013). The concept of Genetic algorithms (GA) has a major difference to other optimisation methods, including conventional optimisation methods and other stochastic research methods (such as ant colony systems, particle swarm, shuffled frog leaping, and memetic algorithm) (S. Mirjalili, 2018). The fundamental difference is that while other methods always explore single points in the search space, GA provides a population of potential solutions (Renner & Ekárt, 2003). In this scenario, the exploration process is continued until a stopping criteria is satisfied or the number of iterations exceeds a certain limit (Arora, 2012). Exploring between ranges of solutions is potentially more efficient in terms of revelation and comparison than following a trajectory based on single solutions toward a good solution (Turrin et al., 2011). Therefore, population based exploration algorithms are more efficient (Chalabee, 2013). In this process, genetic operators including Reproduction, Crossover and Mutation control the generation and evaluation process (S. Mirjalili, 2018):

- **Reproduction**: generates new populations from the existing population
- **Crossover**: swaps two random chromosomes to generate a new solution
- **Mutation:** a small random tweak in the chromosome to maintain the genetic diversity

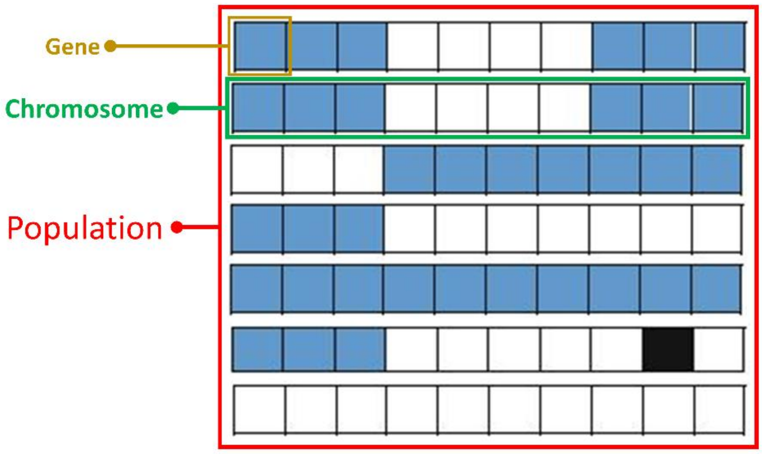


Figure 11: Introduction to Genetic Algorithm (GA)

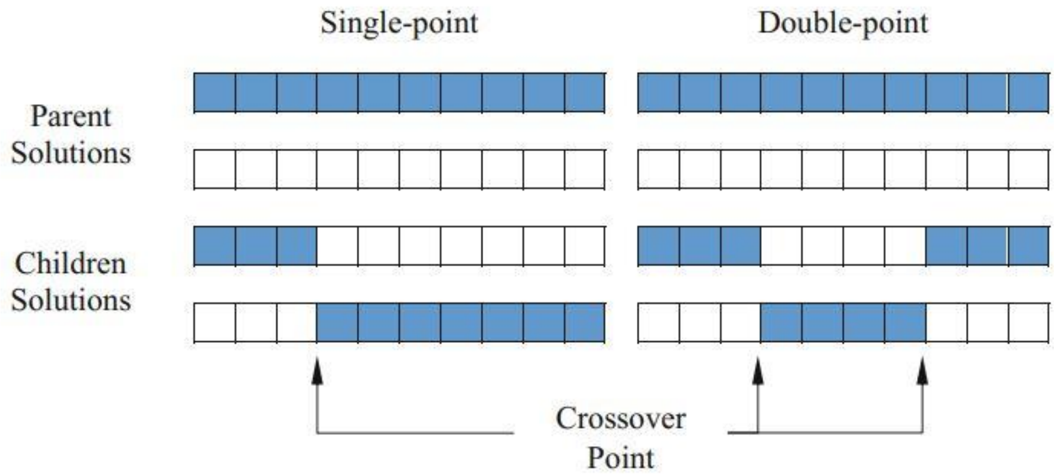


Figure 12: Two popular crossover methods in GA: single-point and double point (S. Mirjalili, 2018)

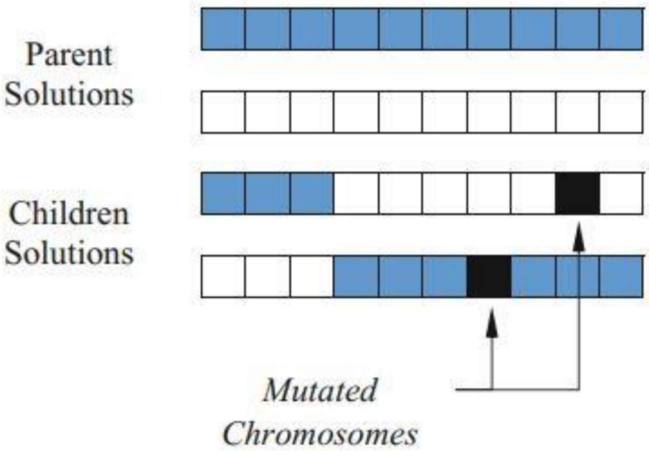


Figure 13: Mutation operator alters one or multiple genes in the children solutions after the crossover phase (S. Mirjalili, 2018)

Existing literature indicates that GA received more attention than other stochastic methods (Darko et al., 2020; Shukla, Janmaijaya, Abraham, & Muhuri, 2019). Table 5 provides samples of research, which used GA for optimisation.

References	**Area**
Merrell et al. (2010)	Computer-Generated Residential Building Layouts
Nordin et al. (2013), Duarte (2005)	mass customization
(J. Wang & Ghosn, 2005) (Deng, Ghosn, & Shao, 2005) (Saravanan, Balamurugan, Sivakumar, & Ramabalan, 2014)	Structural reliability
(Hasançebi, 2007) (Elbehairy, Elbeltagi, Hegazy, & Soudki, 2006)	Bridge design
(X. Zhu et al., 2015)	Composite truss
(Gandomi, Kashani, Roke, & Mousavi, 2017)	Retaining wall
(Senthilkumar, Kannan, & Madesh, 2017)	flux-cored arc welding process
(Reed, Minsker, & Goldberg, 2003) (Erbatur, Hasançebi, Tütüncü, & Kılıç, 2000) (Toğan & Daloğlu, 2006) (Rahami, Kaveh, Aslani, & Najian Asl, 2011) (Khatibinia & Naseralavi, 2014) (Leandro Fleck Fadel Miguel, Lopez, & Miguel, 2013)	Truss optimisation

Table 5: Reviewed extant researches in Civil Engineering using Genetic Algorithm (GA)

2.3.1.2 Visual programming languages (VPL)

Visual programming is a type of computer programming where users graphically interact with program elements instead of typing lines of text code (Konis, Gamas, & Kensek, 2016). Examples include GenOpt (Wetter, 2001), Simulink (Mathworks, 2015), Grasshopper (S. Z. Mirjalili, Mirjalili, Saremi, Faris, & Aljarah, 2018) and Dynamo (Dynamo BIM, 2019). Currently, the use of Grasshopper in conjunction with Rhino is a leading example of a VPL environment, but Dynamo indicates considerable promise in becoming a constructive tool to complement BIM, 3D modeling, and analysis programs (Kensek, 2015). In the visual programming environment, different nodes including numbers, sliders, operators, functions, list manipulation tools, graphic creators, scripts, notes, customizable nodes and packages are connected together virtually by wires to perform a specific function (Konis et al., 2016). Although VPL tools are being widely used in other areas, it has only recently become an important supplement to 3D geometry modelling tools in AEC industry (Kensek, 2015). This method helps to design complex geometric shapes in design tools such as Revit and to evaluate their strength in analysis tools such as Robot Structural Analysis (Kalmykov, Gaponova, Reznik, & Grebenchuk, 2017). Furthermore, the growing progress in Information Technology (IT) provides new opportunities to use VPL tools in calculation, analysis, evaluation and consequently structure optimisation. Table 6 indicates examples of using VPL tools in AEC industry.

References	**Aims**	**VPL tool**	**Area**
(Chlosta, 2012)	Topology and shape optimisation in bridges	Grasshopper	Bridges
(Briscoe, 2014)	Propose a new design proses by using green wall pilot test	Dynamo	Urban infrastructure

(Nourbakhsh, 2016)	Facilitate optimisation of complex buildings	Dynamo	Bridge, Dome, High-rises, Trusses,
(Kalmykov et al., 2017)	Use of information technologies for energetic portrait construction of cylindrical reinforced concrete shells	Dynamo	RC shells
(Bortoluzzi et al. (2019)	Generate BIM models for energy simulation and day-to-day building operations and facility management	Dynamo	Buildings

Table 6: Extant research in Civil Engineering used VPL in design

2.3.1.3 Dynamo

Dynamo was developed as a plug-in for Revit and Vasari that displaces graphical interface for adding and adjusting parametric functions of BIM components (Kensek, 2015). It was developed by Ian Keough to provide a code playground for building interesting parametric functionality (Soto Ogueta, 2012). The motivation or user need for developing Dynamo was exploratory nature (Keough, 2020) and there was no particular problem or requirement to solve through the development of the application (Soto Ogueta, 2012). Dynamo includes parametric geometries and works with Revit, a leading BIM software program (Kensek, 2015). Dynamo for Revit is an open source visual programming platform that enables the user to produce 3D geometry in the Dynamo environment called “graph” (Dynamo, 2020). Moreover, Dynamo enables the user to edit the parameters of a family in Revit and view the results in the Revit environment simultaneously (Kensek, 2015). This smooth integration enables designers to generate all forms of complex geometries (Skolan, Arkitektur, & Samhällsbyggnad, 2016).

Optimo

This research used Optimo for the optimisation part of the prototype. Optimo is an open source Multi-Disciplinary Optimisation (MDO) visual programming interface tool (package) which is developed by Rahmani Asl (2015). It particularly interacts with Autodesk Revit to generate efficient design space exploration for achieving high-performance buildings. It is developed as a package that can be installed in Dynamo and performs based on Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (Deb, Pratap, Agarwal, & Meyarivan, 2002). Optimo uses variables with lower and upper domains as design parameters (Rahmani Asl, 2015) to generate alternative solutions within the required domain. One of the main benefits of Optimo is that the user interface is a visual programming environment, which considerably facilitates the parametric modelling and simulation process for architects and engineers who have limited computer programming background (Rahmani Asl, Zarrinmehr, Bergin, & Yan, 2015).

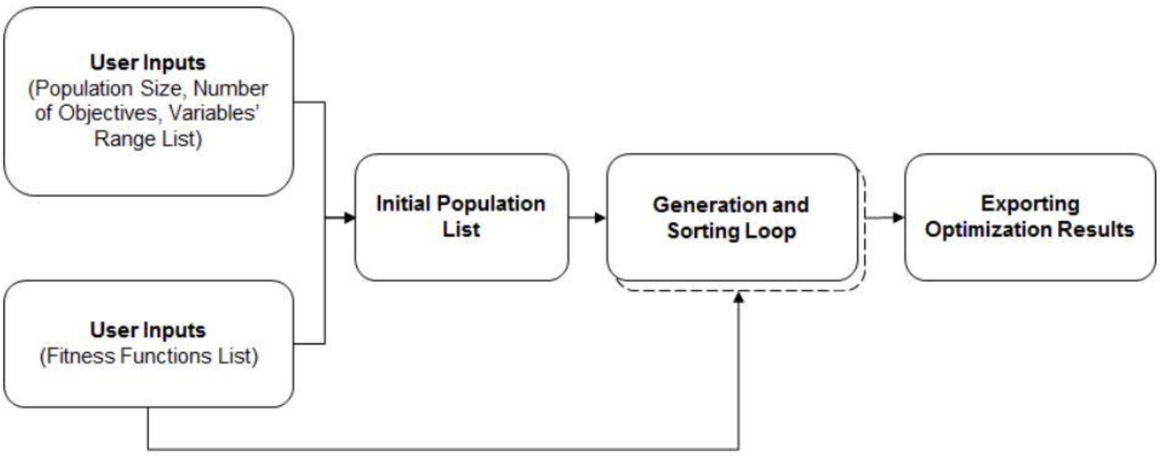


Figure 14: Flowchart demonstrates the workflow of the Optimo (Rahmani Asl, Stoupine, et al., 2015)

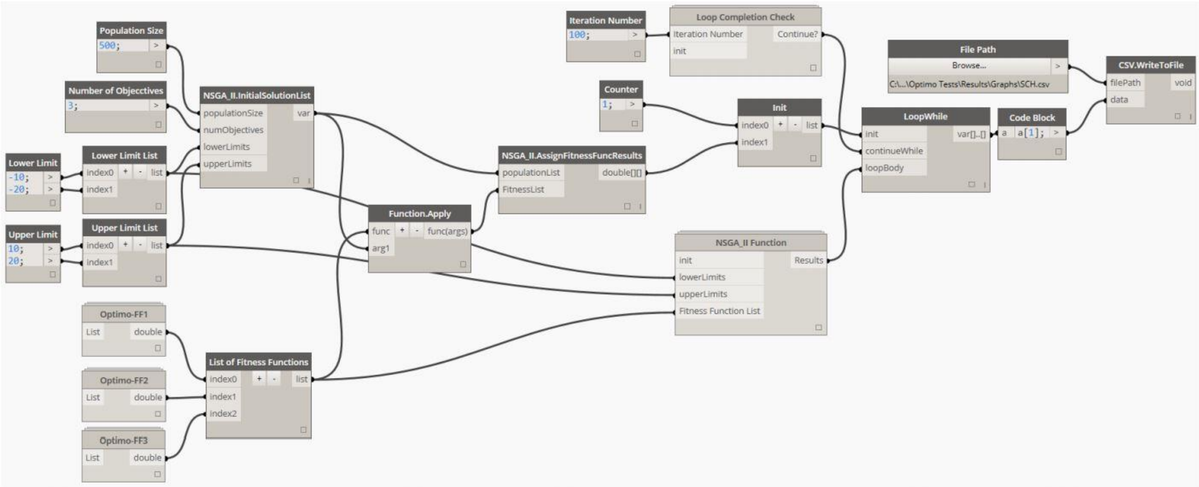


Figure 15: Optimo custom node consists of several nodes in Dynamo (Asl et al., 2015)

2.4 Summary

The key output of this literature review is the identification of the existing challenges during the structural design, analysis and optimisation process and the integration between the structural engineers and architects. Thereafter, potential solutions to the identified challenges were explored to develop a Conceptual Structural Design Optimisation (CSDO) framework. Therefore, this chapter was divided in three sections: 1. Structural Design 2. Building information Modelling (BIM) 3. Artificial Intelligence (AI). The first section details the structural design and optimisation process, highlight the recent progress of the structural design process, and explains the existing challenges. The second section details the BIM technology and application of BIM in the AEC industry and highlights the advantage of BIM-enabled structural design. This section explains how BIM technology can be used to solve the existing challenges. The third section provides a comprehensive information about the Artificial Intelligence (AI), Generative Design (GD), Genetic Algorithms (GA) as a potential solution proposed in this research to solve the highlighted challenges. According to the extant literature the integration between structural engineers and architects is a fundamental aspect, which requires new tools and methods to overcome technical challenges (Issa & Olbina, 2015). To establish the automated synergy needed, the research drew upon the capabilities of visual programming – to create the technically automated link between architectural and structural design procedures. In parametric BIM, the visual programming interface can replace the conventional elaborate coding with visual small blocks, which work independently to perform certain tasks. Visual programming enables designers to develop computer programs by manipulating visual blocks and linking them graphically rather than using coding – this is much easier for users with no programming background. Recent developments in building design technology offer a new opportunity to use visual programming tools for designers. Chief among all available tools are Grasshopper (Grasshopper, n.d.; S. Z. Mirjalili et al., 2018) and Dynamo (Dynamo BIM, 2019). This research uses Dynamo as it performs more efficiently with Autodesk Revit (hereafter referred to as Revit) and extends the power of Revit by readily providing access to the Revit API (Application Programming Interface). In the design process, Dynamo synchronises the parametric data of the architectural model into the structural design platform to design different alternative structural models. The main advantage of this automatic synergy is that all generated structural models are based on the architectural model's boundary conditions and any change in the architectural model will update structural models – automatically.

As discussed, the second need of structural engineers is to reduce the demanding tasks related to the iterative processing of structural design. The proposed prototype is developed on a BIM-based platform to facilitate data exchange and create synergy between structural and architectural models. That is, BIM tools enable designers to use parametric data to model 3D geometric shapes. Hence, the proposed toolset can generate alternative structural models using geometry parameters (from Revit) and rules (in Dynamo). This allows designers to automatically update the structural models according to any change of architectural model parameters.

Chapter 3: **Methodology**

This chapter provides an overview of the research philosophy, which guides the methodology, and justify the methods adopted in this thesis to achieve the research aim and objectives.

This chapter also details the validation of the framework and prototype, which includes the development and results of the online questionnaire, and interviews. The questionnaire helped to gather valuable information about the existing challenges, and potential solutions that justified the research knowledge gap and helped to purposefully develop an extended framework and a proof of concept prototype. Thereafter, the prototype was validated through an online interview and focus group to demonstrate the workability of the prototype.

3.1 Introduction

According to Easterby-Smith, Thorpe and Jackson (2012), there are number of fundamental reasons for considering the philosophical aspects of research. Initially, understanding the philosophy enables the researcher to find an appropriate research design and distinguish which design will be more practical. Moreover, it can assist the researcher to produce new research designs. Hence, these reasons highlight the importance of understanding of the philosophy of the research design to solve different issues during research process. The essence of this research is to assist structural engineers at the early stage of design in the BIM platform. In doing so, it is essential to investigate current structural design and BIM practices, and then demonstrate how the proposed research will improve it. This chapter provides a detailed description and justification of the methodology employed throughout the research before describing the data collection and analysis methods in detail. It first establishes the philosophical position of this research and then, identifies the appropriate methodology and resulting methods for collecting and analysing data. The methodology for the validity and reliability of the data analysis is then discussed. The chapter also presents a summary of the data collection's ethical considerations.

3.2 Research Application

Gratton Jones (2014) argued that according to the context of the research, it can be classified as pure research or applied research.

Pure research in most cases is driven purely by the curiosity and desire to add knowledge to the existing literature and expand it (Gratton & Jones, 2014). The main aim of this research application is specifically to gain information and contribute to the knowledge and existing literature, hence, any particular beneficial outcomes of the research are a bonus (Goddard & Melville, 2004). Applied research, is concerned with solving a particular problem or providing a solution to a specific question (Gratton & Jones, 2014).

This research adopted both pure research and applied research applications to provide comprehensive information of the existing structural design and optimisation processes and BIM technology, highlight the existing challenges and provide a framework, which presents potential solutions to solve the problems. In this process, the research starts as a pure research application by using the existing literature and similar works with the aim of highlighting the current gaps in the structural design and optimisation process and interoperability between architects and structural engineers and designers. The research carried out as an applied research application with an extensive literature review aiming to provide solutions to the highlighted challenges. Moreover, automatic design, generative design and BIM technology were investigated as potential solution to the existing challenges. Consequently, this research proposed a Conceptual Structural Design Optimisation (CSDO)

Framework as a potential solution to the highlighted challenges. In addition, this research provides an extensive literature review regarding optimisation of structural design and Building Information Modelling/ Management (BIM) technology and interoperability between architects and structural engineers and designers as a contribution to the existing knowledge. Furthermore, this research used applied research application through empirical means based upon surveys, measurements and observations to validate the CSDO framework and develop an extended version of SDO framework and consequently a proof of concept prototype. Therefore, this research uses applied research application to provide an automatic system that efficiently facilitates the conceptual structural design and optimisation process in BIM particularly at the early stage.

3.3 Research Objective

The research objective or the purpose of research is to discover answers to questions and explore the truth, which are hidden and have not been discovered yet through the application of scientific procedures (Kothari, 2004). There are different classification criteria for research objectives such as the process of specifying key features that describes the research aim (Ahmad, 2014), data collection and data analysis (Gratton & Jones, 2014) falling into a number of following groupings: exploratory, correlation, descriptive and explanatory.

The focus of this research is the automatic integration between architectural and structural design and optimisation of the structural design in BIM platform by using automation. This combination is one of the novelties of this research and the existing literature has limited information in this area especially automatic interoperability and integration between architects and structural engineers. Therefore, this research starts with the exploratory objective to achieve familiarity with the phenomenon of automatic design and interoperability between architects and engineers and gain a new insight into this area. This research started with very limited preconceived ideas and followed up with more research to scope out the magnitude and extent of the phenomenon of automatic design and interoperability. As an outcome of the exploratory research objective, a Conceptual Structural Design Optimisation (CSDO) Framework was developed. Moreover, a comprehensive literature review regarding using automation in structural design, optimisation process and interoperability between architects and engineers was conducted that provides a new insight, which contributes to future research and development. On the top of the exploratory research objective, a correlation research objective is used to compare the proposed framework with the traditional process of the structural design and optimisation and the interoperability between architects and engineers.

3.4 Research World View

A number of studies defined the research world view (also called paradigms) as a theoretical outline or structure that guides how research is viewed and approached by different researchers (Fellows & Liu, 2015; Lincoln et al., 2011; Mertens, 2014). Existing literature related to the research methods, highlighted that there are different philosophical worldviews or perspectives such as positivism, interpretivism, realism, objectivism, constructivism and pragmatism. Although, it is notable that positivism and interpretivism are two main perspective philosophical traditions. All these traditions based on different worldview or paradigmatic aspects of Ontology, Epistemology and Axiology. Therefore, a worldview guides researchers to ask particular questions and use appropriate methods to systematic inquiry known as methodology (Schwandt, 2001).

Ontological Considerations

Ontology philosophy deals with the nature of reality and it refers to how the research will answer the questions (Withana-Gamage, 2011). This philosophy answers to the questions: ‘’what is reality?’’

(D Byrne, 2017) can be classified into three categories: objective, constructive and pragmatic (K. P. Kim & Park, 2013).

Epistemological Consideration

Epistemology philosophy is concerned with questions "how the researcher knows the reality" and ''how can I know the reality?'' (Creswell & Creswell, 2018). Therefore, it is known as the study of knowledge (D Byrne, 2017). Epistemology and methodology are two intimately related concepts in research philosophy. Epistemology involves the philosophy of how we come to know the world while methodology involves the practice to find the reality (William, 2008). Often, epistemology breaks down to subjectivism, positivism, post-positivism realism and interpretivism (K. P. Kim & Park, 2013).

This research had an axiological consideration to articulate the researcher's values (beliefs) as a foundation to make a decision about the research conduction and development. In terms of data collection, the research started with an ontological consideration to achieve knowledge and information of different phenomenon related to the research i.e. structural design, optimisation, Building Information Modelling (BIM), collaboration etc. In this scenario, a constructivism worldview was adopted for learning and enhancing the overall knowledge in the research area. Because constructivism is based on the observation and scientific study about people's experience of a phenomenon and how they learn and reflect on those experiences (WNET education, 2004). Based on the obtained knowledge and information, post-positivism worldview was adopted to develop a framework and proof of concept prototype to demonstrate the concept and workability of the concept.

3.5 Research Approach

Once the research philosophy is determined, the research approaches need to be considered. A research approach is often classified into two contrasting approaches of deductive and inductive (M. N. K. Saunders, 2019).

Deductive approach begins with theory, often developed from literature review, and the research strategy helps to test the theory (M. N. K. Saunders, 2019). In this approach, appropriate data collection helps the researchers to measure the concepts and analyse them. The inductive approach begins with data collection to explore a phenomenon and accordingly the researcher generates or builds a theory (often in the form of a conceptual framework) (M. N. K. Saunders, 2019). The aim of this approach is to achieve a better understanding of the nature of the problem. In this approach, data analysis helps to formulate a theory, often proposed as a conceptual framework to make better sense (M. N. K. Saunders, 2019). The abductive approach is a combination of deductive and inductive approaches, rather than moving from theory to data (deductive) or data to theory (inductive) (M. N. K. Saunders, 2019). In this approach, data collection is used to explore a phenomenon, identify themes and explain a pattern to develop a new or amend the current theory, which is tested through additional data collections (Ketokivi & Mantere, 2010).

This research uses an abductive approach by using data collection to explore the existing challenges in the structural design and optimisation process through the existing literature and provide a potential solution to solve the challenges. Thereafter, it proposes the solution in a form of a conceptual framework and validate it in subsequent data collection i.e. questionnaire and interview.

	Deductive	Inductive	Abductive

Logic	In a deductive approach, when the premises are true, the conclusion must be true	In an inductive approach, premises are used to develop **untested** conclusions	In an abductive approach, premises are used to develop a **testable** conclusion
Generalisability	Generalising from the general to the specific	Generalising from the specific to the general	Generalising from the interactions between the specific and the general
Use of data	Data collection is used to test and evaluate premises related to the theory	Data collection is used to explore the phenomenon, identify themes and patterns and generate a framework	Data collection is used to explore a phenomenon, identify themes and patterns, propose it in a conceptual framework and validate it in subsequent data collection
Theory	Theory validation	Theory generation	Theory modification and/or modification.

Table 7: Details Deduction, Inductive and Abductive approach in terms of logic generalisability, use of data and theory

3.6 Research Strategy

Research strategy is the methodological link between research philosophy and the subsequent choice of methods to collect and analyse data to answer the research questions (Denzin & Lincoln, 2018). Existing literature demonstrated that there are different classifications available for research strategies. For example,. Saunders (2019) classified the research strategy into eight different strategies including experiment, survey, case study, action research, ground theory, and ethnography, archival and narrative inquiry. Survey research strategy is defined as ‘’the collection of information from a sample of individuals through their responses to questions’’(Check & Schutt, 2011). This strategy enables the researcher to use various methods to recruit participants, collect data and analyse them (Ponto, 2015). Normally, the purpose of a survey is not to consider a particular case in depth but to gain the main characteristics of the population at any given moment, or to monitor any changes over time (Tan, 2002). Therefore, surveys are suitable for receiving suggestions on possible reasons for a specific relationship between variables; providing models of these relationships; and generating the findings that are representative of the whole population (M. N. K. Saunders, 2019). Survey design can use qualitative methodologies (e.g., using open-ended questions), quantitative methodologies (e.g., using questionnaires with numerically rated items) or mixed methods (Ponto, 2015). Survey strategy using questionnaires are popular as they allow the data collection from a large number of the population (M. N. K. Saunders, 2019). Case study research strategy is an in depth inquiry into a phenomenon within its real life setting (Yin, 2017). The case in a case study may refer to a person, group, organisation, event or process. Hence, deciding on the case to be studied and relevant boundaries are the main criteria to perform a case study (M. N. K. Saunders, 2019). R. k. Yin (2017) stated that case studies can be used in descriptive, exploratory and explanatory research by using various data collection methods including interview, observations, documentary evidence and questionnaire (Gerring, 2006; M. N. K. Saunders, 2019).

This research used survey and case study strategies. Survey strategy was used to justify and validate the research, which includes an online questionnaire and a semi-structured interview. The aim of the questionnaire survey was to highlight the existing challenges in the industry and provide potential solutions to help to solve the challenges. Moreover, the interview survey was conducted between the professionally accredited structural engineers in the UK. The aim of the interview was to validate the proposed framework and prototype and demonstrate the generalisability of the process by applying the prototype in a case study.

3.7 Research Methodology

Research methodology is the general plan of how you will go about answering the research questions. After deciding the right approach to answer the research questions by using research philosophy and research approach, research methodology focuses on the process of research, and how to turn the research question into a research project (M. N. K. Saunders, 2019). Tan (2002) described the research methodology as a continuous process for getting from the research questions to the conclusion. Moreover, a research methodology provides guidelines that connect different elements of the research. For example, it can link the paradigm to the research strategy and then the strategy to the methods used for the data collection (Denzin & Lincoln, 2018). Therefore, research methodology can be described as a process of data collection and data analysis in order to answer the research questions (Bell, Bryman, & Harley, 2018). The initial methodological decision is to choose between qualitative, quantitative or mixed method (Creswell & Creswell, 2018).

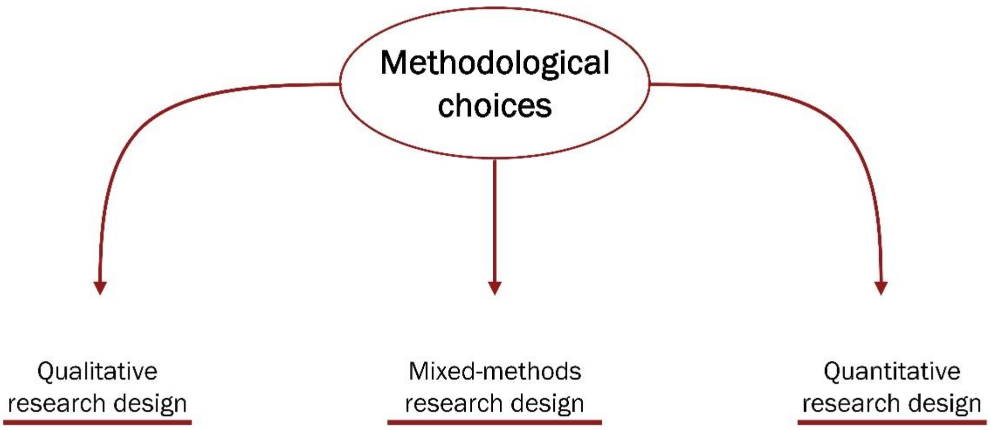


Figure 16: Methodology classification in three groups of qualitative quantitative and mixed method.

Qualitative research methodology is normally associated with interpretive and constructive worldviews, because the researcher needs to observe a phenomenon and make sense of the subjective and socially constructed data (Kawulich & Chilisa, 2015; M. N. K. Saunders, 2019). Qualitative research uses various data collection methods to collect information from the participants in the research and uses various data analysis methods to analyse the received data and develop a conceptual framework and theoretical contribution (M. N. K. Saunders, 2019). Quantitative research methodology is normally associated with the positivism worldview, especially when the data collection process is highly structured (Kawulich & Chilisa, 2015; M. N. K. Saunders, 2019). Quantitative research may incorporate with a deductive or inductive approach, where data are collected and analysed to test a theory or develop a theory (M. N. K. Saunders, 2019). Quantitative research evaluates relationship between variables, which are measured and analysed numerically using a range of statistical and graphical methods. Mixed Method Research (MMR) methodology a type of multiple methods research that uses qualitative and quantitative data collection and data analyses in the same research (M. N. K. Saunders, 2019). MMR combines qualitative and quantitative methods in different ways, which lead to the identification of a number of variations of MMR including simple (concurrent) and complex (sequential) (Creswell & Plano-Clark, 2011). Concurrent MMR uses separate qualitative and quantitative methods for data collection and data analysis in a single phase, while sequential MMR includes more than one single phase and it uses the findings of one method to begin other method and expand the initial findings (M. N. K. Saunders, 2019).

This research used a sequential explanatory mixed method research methodology to highlight the existing gaps in the structural design process in the current industry and develop a conceptual framework to solve the gaps (qualitative). Thereafter, the conceptual framework was validated and an extended framework was developed. Finally, the workability of the extended framework was demonstrated through a proof of concept prototype (quantitative).

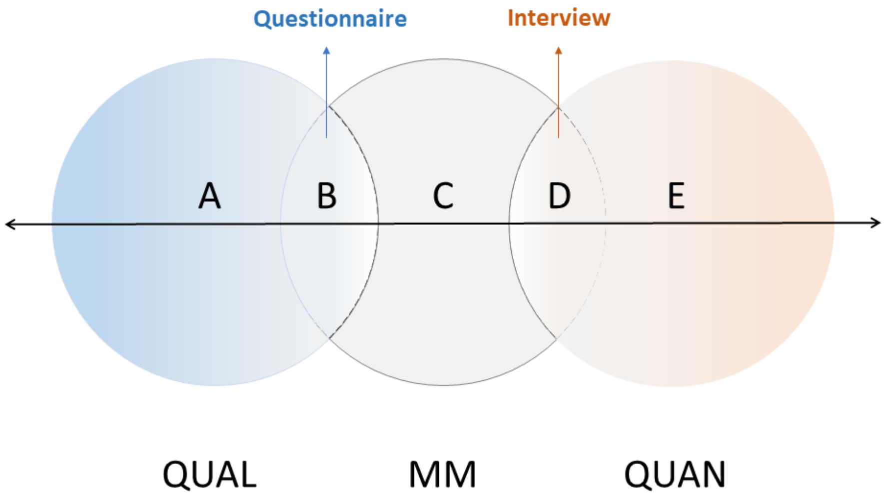


Figure 17: Sequential exploratory MMR is used to explore the exising challenges at the early stage of the structural design using a comprehensive literature review (A), develop a conceptual structural design framework based on the information achived from the literature review and validate the framework through an online questionnaire (B). Based on the results of the data analysis of the responses to the online questionnaire the extended version of the frame work was developed (C). Thereafter, a proof of concept prototype was developed to show the workability of the extended framework (D). The proposed prototype was validated in different interview (E).

3.8 Research Methods

Research methods are techniques or procedures used to approach objectives of the research, collect and analyse data related to a research question(s) or hypothesis (David Byrne, 2017). They may include a particular instrument for data collection for example, completion of questionnaires, interviews, observation techniques, analysis of the existing literature and simulations (Withana-Gamage, 2011). The following subsections detailed all the methods of the data collection and data analysis which are used in this research.

3.8.1Questionnaires

The literature review highlighted the lack of automation in structural design and optimisation, and integration between architectural models and structural models. Although, it has emphasised the requirement for research in this area. As a part of the exploratory research, a questionnaire survey was adopted for data collection to capture a broad view on the research knowledge gap and provide potential solutions to the explored gaps. Formulating appropriate questions to explore areas of interest is key to being successful in surveys. Table 8 explains different types of questions such as open questions, probing questions, specific and close questions and few relevant examples, which are used in this research.

Type of question	Definition	Examples
Open questions	These questions encourage the interviewees to define and describe a phenomenon or topic as they wish and enable the researchers to obtain facts.	• What are the existing challenges in industry? • How do engineers tackle the challenges? • How can BIM and automation help to solve the challenges?
Probing questions	These questions help to explore areas with a particular focus on the research topic. In addition, this type of questions can be used when the response is not clear.	• How would you solve the challenges? • How would you evaluate the success of this work in the current industry? • That is interesting; would you explain more?
Specific questions	These questions seek information in specific areas to start questioning about a particular topic.	• Would you tell me about the use of BIM in the structural design process? • How do you optimise the structural design during the early stages?
Closed questions	These questions may be used to confirm a fact or opinion.	• Do you think BIM and automation can be helpful in structural design? • Do you think Generative Design (GD) can help the

	optimisation of the structural design process?

Table 8: Different types of questions, which are used in this research to explore the existing challenges at the early stage of the structural design and find potential solutions to solve the challenges.

3.8.1.1 Questionnaire Design and Development

The questionnaire was divided into five sections and included various types of questions (table 9) starting with quantitative questions (closed-ended questions) and finishing with qualitative questions (open-ended questions). The first section includes the research information and invitation letter, followed by demographic information in the second section. The third section focuses on structural design and analysis, the fourth section is about BIM, and the fifth section thanks the respondents for participating in the survey (Table 9). This table shows that the questionnaire used seven different types of questions in two forms of open-ended and closed-ended questions. This variety of the questions helped to achieve the required information from the respondents and convince them to complete the questionnaire by preventing the fatigue of response to a long questionnaire. Moreover, at the end of the questionnaire, the respondents were asked to leave their email address if they are interested in contributing to the future work and prototype validation.

Question Form	Question Type	Number of Question	%
	Multiple Choice	9	
Closed-ended	Check Box	4	77%
	Linear Scale	2	

	Multiple Choice Grid	4	
	Tick Box Grid	1	
Open-ended	Short Answer	1	23%
	Long Answer	5	
Total		26	100%

Table 9: Number and percentage of each type of question in the questionnaire.

3.8.1.2 Pilot Test

The internal validity and reliability of the data collection and response rate highly depends on the questionnaire design and the rigour of the pilot study (M. N. K. Saunders, 2019). Therefore, before a questionnaire is distributed it should be piloted by small scale sample of relevant respondents to ensure the clarity and validity. The feedback received from the pilot study provides the opportunity to improve the questionnaire and determine the required time to complete it, and ultimately, this increases the reliability level of the questionnaire. Thus, a pilot survey was carried out in two stages; initially, the pilot questionnaire was conducted amongst 14 PhD students and after amendments, the improved version of the questionnaire was piloted among 10 academic staff of the School of Civil Engineering and surveying (SCES) at the University of Portsmouth. The latter group was asked to comment on the suitability of the questions to be distributed between industries. Therefore, a considerable number of suggestions were received to make necessary amendments on the structure of the questionnaire, which helped to stablish the content validity of the questionnaire. Consequently, the pilot study demonstrated that the questionnaire took 15-20 minutes to complete. The feedback received from the pilot respondents showed that the framework procedure (flowchart) was not clear and required more detailed explanation. Therefore, the flowchart was removed from the online questionnaire and was added to the interview and focus group with more time for detailed explanation of the framework process since explanation of the framework would increase the time required to answer the questionnaire and consequently, reduce the response rate. Therefore, the flowchart was replaced with more questions targeting different aspects of the framework. Moreover, the wording of the questionnaire was improved and grammar mistakes were corrected, a few questions were adjusted to include more details and ensure clarity. Finally, the pilot survey was revised and the main survey was conducted.

3.8.1.3 Questionnaire Sampling

This research required participants with structural engineering background and/or BIM experts. Therefore, the research population decided to be the professionally accredited members of the Institution of Structural Engineers (IStructE), the Institution of Civil Engineers (ICE) and the American Society of Civil Engineers (ASCE) in the UK and the US. This research has used both non-probability and probability for the sampling strategy to receive detailed information on the current structural design process (in BIM), available issues during the structural design process and potential solution to solve the issues.

Therefore, non-probability sampling, which samples the population in a strategic way in combination with purposive, quota and snowball strategy, was used to circulate the questionnaire between people with relevant subjects. The purposive sample was used to distribute this questionnaire between structural engineers and BIM experts who are known to the researcher and who are part of a professional network such as IStructE, ICE and ASCE. The quota sample includes structural engineers and BIM experts who were identified as members of professional committees or groups. This research used quota sampling to distribute the questionnaire between committee members of the southern region structural engineers of the IStructE and structural engineering groups in LinkedIn. On the other hand, probability stratified sampling was used to approach the target samples. In this scenario, the IStructE website was used to approach the most relevant companies in the southern region (Figure 18). Thereafter, all the companies were asked to circulate the questionnaire only between structural engineers and BIM coordinators.

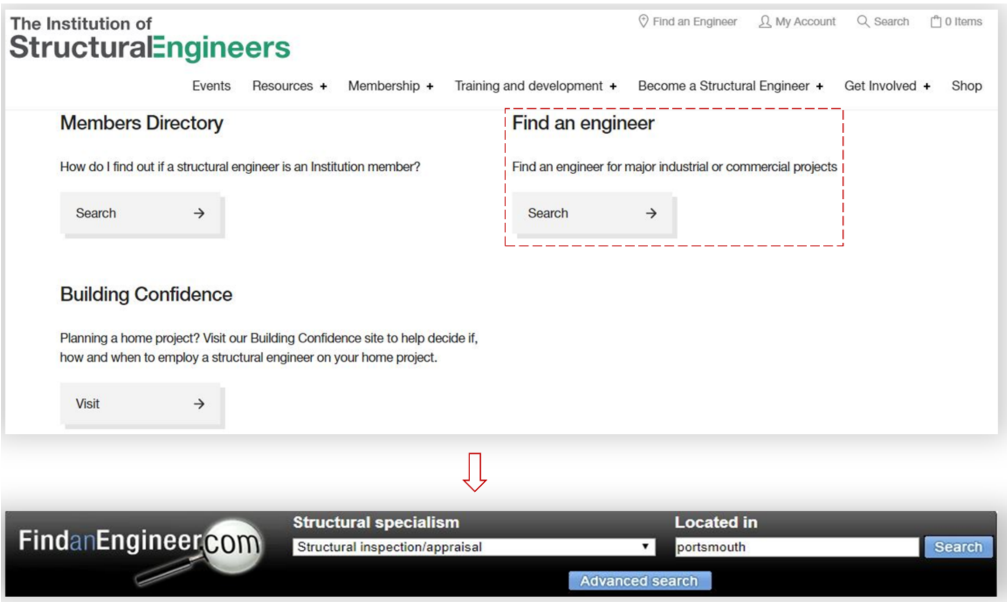


Figure 18: IStructE website was used to approach the members of the institution

Moreover, snowball sampling is adopted to expand the survey and receive more detailed information. In this scenario, since the research population (chartered structural engineers with knowledge of BIM) is not easily accessible also to expand the research sample size, all the respondents were kindly asked to share the link of the questionnaire with other structural engineers / BIM experts in their network who might be interested in the survey.

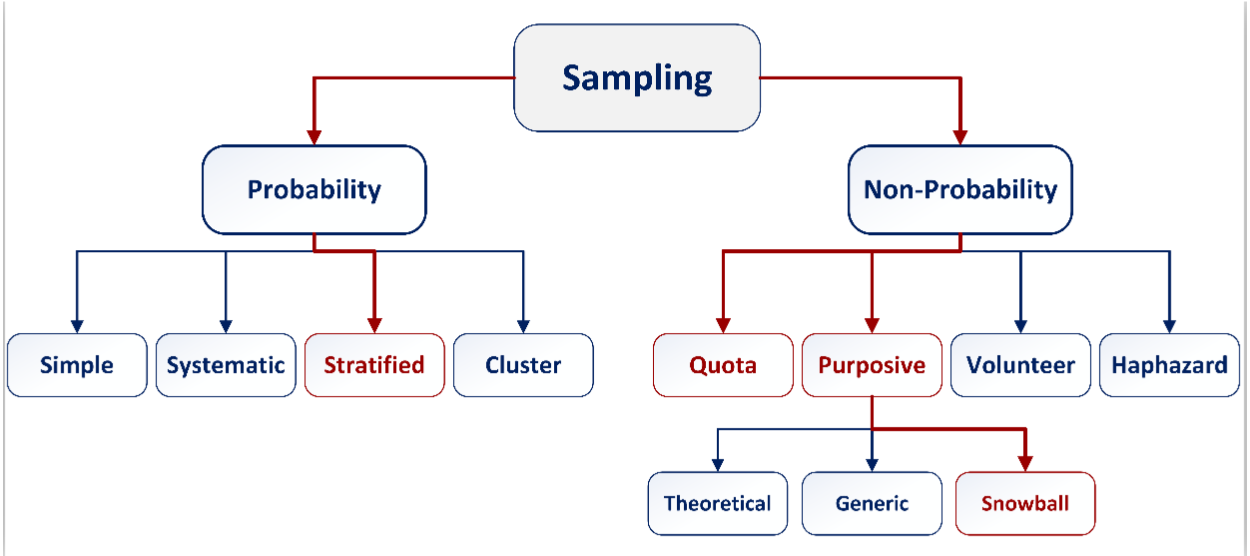


Figure 19: The sampling strategy, which is used in this research to distribute the questionnaire.

3.8.1.4 Questionnaire Sample Size

Contact details of the respondents were collected from three main sources including IStructE, LinkedIn and the similar publications. This research focused on the UK and Ireland regional groups of the IStructE, which involve 21 regional groups with a committee panel of structural engineers in each region, which are considered as the main research population. The 'FindanEngineer' section of the website was used as a comprehensive database of structural engineering practices across the UK. This scheme, only registers firms that have at least one member from the IStructE and demonstrates available companies in specific areas. Moreover, the 'Member's directory' section was used to search for specific members of the Institution by entering details of the members. The researcher purposefully reached these members, as they are experts in the field and their contribution to the questionnaire provides a great value to the research.

The quota sample were contacted by publishing the link of the questionnaire in professional groups on LinkedIn such as the BIM community, Revit structural users, BIM Experts, Structural engineers, etc. Additionally, LinkedIn was used as a method of communication to communicate and share information with the experts in the field who had relevant experience and could contribute to the research. A total number of 354 questionnaires were distributed amongst professionally accredited structural engineers of the IStructE, ICE and ASCE. All the questionnaires were emailed or sent on LinkedIn. A reminder email or message were sent to all the non-respondents questionnaires every two weeks for two months. Figure 20 demonstrates the growth of received responses from the respondents. This figure shows three peaks of 11, 7 and 16 responses after every two weeks, which shows the effect of the regular reminders for non-respondent questionnaires. In total 107 questionnaire responses were received at the end of second month of data collection.

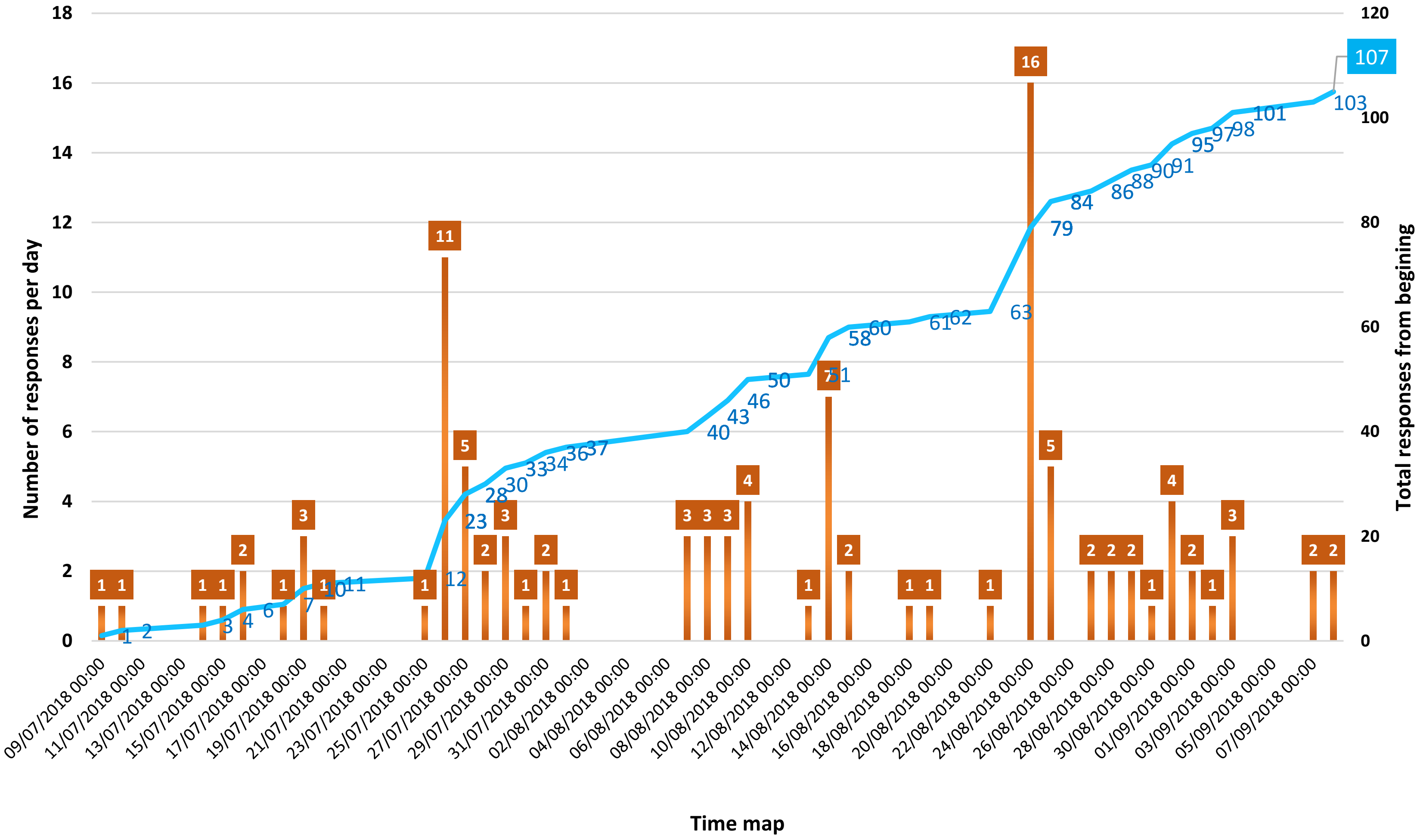


Figure 20: Total responses to the questionnaire during the time of the data collection

3.8.1.5 Strategies adopted to increase the response rate

According to Fellows & Liu (2015) data collection requires a careful statistical design to obtain sufficient expected responses to satisfy the validity through sample selection and sizing. Thus, special attention was given to the questionnaire design and administration process to maximise the response rate. Therefore, the questionnaire was designed with different types of questions and was limited to six pages to minimise the response time. Moreover, a pilot study was conducted to ensure the clarity of the questionnaire. During the distribution of the questionnaire an effort was made to identify the population by their name and level of expertise to conduct reliable information. Additionally, snowball sampling helped to approach the more professionals who are relevant to the research area. Furthermore, the questionnaire was distributed with the University of Portsmouth logo in the heading as an effective way of attracting respondents by ensuring confidentiality and reliability. According to Fellows & Liu,(2015) an acceptable conclusion requires a sufficient response rate. According to equation 1, the active response rate of the questionnaire is 30.22%.

$$Active\ response\ rate = \frac{Total\ number\ of\ responses}{Total\ number\ in\ sample - (ineligible + unreachable)}$$

$$Active\ response\ rate = \frac{107}{354} = 30.22\%$$

Equation 1 : Active response rate

The result of the data analysis of the response to the online questionnaire provided valuable information to amend the conceptual framework and provide and extended version of the framework in a form of a proof of concept prototype.

3.8.2Interviews and focus group

The research interview enable the researchers to collect valid and reliable data from trustful sources, which are relevant to the research questions and objectives. The objective of the research at this stage was to validate the workability of the extended framework through a proof of concept prototype. The following are the main criteria that the prototype presents:

- Automatic integrated design between architects and structural engineers
- Automatic structural design based on the architectural model
- Automatic use of the structural analysis results
- Automatic alternative structural design process
- Automatic evaluation and comparison between alternative structural designs by using the extracted information of the structural analysis

Cheng and Atlee (2007) argued that development of a new engineering software requires a validation process in real world application or industry settings to assess the practicality, scalability and ease of application of the system. Therefore, the prototype was validated in the real world setting in BIM platform by using Revit, Dynamo and Robot Structural Analysis (RSA). A pilot interview was conducted prior to the actual interview to eliminate any misleading questions, ambiguity and any difficulty in responding. Thereafter, several semi-structured interviews were conducted as a validation methodology to achieve the research objectives. The purpose of the validation was to assess whether the prototype reflects the aim of the research and to demonstrate the workability of the framework. It was intended that comments and feedback from the professionals in the field would provide efficient information on the appropriateness, suitability, applicability, and ease of use of the prototype. In this case, an already recorded video of the process of the prototype for a residential house was demonstrated to the participants show the workability of the prototype. The video started with a brief introduction about the aim and objectives of the research and the features of the prototype. It was followed by an introduction to the software, which are used in the prototype and explained that how these tools are linked and performed simultaneously in an automatic process. After the introduction, a case study of two story residential building was used to demonstrate the workability of the prototype in a real project. The case study started with an architectural model in Revit without any structural element to show how the proposed prototype is capable of using the architectural information and generating different alternative structural models. Thereafter, the results of the structural analysis were demonstrated to explain how they could be used to compare different alternative structural models and make a more efficient decision. Finally, a questionnaire with 10 open questions were given to the respondents to answer and assess the prototype. The intention of open questions was to achieve important generic factors that interviewees feel may have been missed-out or ignored in the prototype. Furthermore, these open questions allows the free expression of opinions that would have been difficult to obtain with quantitative questions. The video of the prototype was presented to number of structural engineers with strong background and experiences in this field. An approximately 30 minutes interview was arranged with each of the interviewees which included 15 minutes video followed by 10-15 minutes questionnaire and discussion.

In addition to the interviews, a focus group was conducted to further investigate the problem and evaluate the prototype. This focus group gathered six researchers of Autodesk from USA, UK, Poland and Netherland. This meeting was organised by product manager of the Autodesk in Zoom application. The focus group was around 45 minutes. In this meeting after presenting the recorded video about the prototype, individuals expressed their thoughts and feedback. This information were considered to modify and improve the prototype. Furthermore, considerable information were collected to be used for further development and future work. The main drawback of this method of data collection is the direct presentation of the work by the author, which may cause bias. In order to prevent potential bias due to the one-to- one semi-structured interview, all the respondents were encouraged to be objective in their respondents. Furthermore, they were asked to provide feedback about weaknesses of the work and how to improve it. The questionnaire included 10 open questions started with asking general questions and then narrow down to more technical aspects. The following are the questions and the reason they have been asked.

Question 1: What do you think about the prototype/framework?

- Allows the interviewee to mention the most interesting and attractive part of the prototype before start asking more detail questions.
- Allow the interviewee to ask questions if something was not clear
- Allow the interviewee to highlight noticed issues of the work.

Question 2: What did you like more about this prototype/framework?

- Assess the strength of the prototype for further development and future work
- Assess the potential contribution of the prototype
- Assess if the prototype has the potential to addressed the existing challenges

Question 3: Does the prototype/framework facilitate the structural design process?

- Assess whether the prototype met the aim of the research
- Validate the research

Question 4: Do you think the prototype/framework follow a logical order?

- Assess the workability of the prototype
- Assess the practicality in the real world projects

Question 5: Is the process of evaluating and comparing different models clear?

- Assess the prototype in terms of evaluation, decision making and optimisation
- Use the feedback to improve the optimisation process

Question 6: Is it practical for decision making at the early stage to select the best design?

- Assess the workability of the prototype at the early stage
- Assess whether the prototype met the aim of the research

Question 7: Would you like to learn and use it in your projects?

- Evaluate the workability of the prototype
- Assure if the prototype is practically useable in real world projects

Question 8: What are the barriers to adopt this prototype/framework in industry?

- Highlight the practical limitations and try to solve them during future work

Question 9: What would you change in this prototype/framework to improve it?

- Highlight the weaknesses of the prototype and try to solve them in the future work

Question 10: In general, does the system create positive impact in structural design process?

- Summarise the assessment and validation
- Ask if they have anything to share to improve the prototype

3.8.2.1 Sampling

Sample population of the participants in the semi-structured interview was decided to be a mixture of academic and industry professionals in the field of structural engineering. The purpose of this decision was to achieve feedback from both peer and group review. Moreover, purposive sampling was used to select interviewees because the interview requires professional structural engineers with knowledge of BIM. Hence, in total 10 people were invited to participate in the prototype validation interview. Table 10 provides a brief description of the participants. Seven out of ten participants had industrial experience as structural engineer. The other three participants are from academic background with knowledge of structural design and BIM. Although the sample size may not adequately represent the number of structural engineers in industry, but the responses received from the participants are the key required information to validate the proof of concept prototype and in total the framework and research. Furthermore, the feedback and comments received from the participants is adequate to improve the framework as it is developed at a proof of concept level.

Participants	Background	Qualification	Years of experience
P1	Industry	Charter – ACSE	17
P2	Industry	Charter – IStructE	11
P3	Industry	Charter – ICE	20
P4	Industry	Senior engineer	20
P5	Industry	Senior engineer	15
P6	Industry	Head of Digital Services	20
P7	Industry	Senior engineer	16
P8	Academia	PhD – lecturer	19
P9	Academia	PhD – lecturer	6
P10	Academic	PhD – lecturer	20

Table 10: Background of the participants in the interview.

3.8.2.2 Response rate

All the participants in the interview and focus group were encouraged to answer to the questionnaire during the interview to increase the response rate. However, several participants decided to send back their response to the author. Finally, all the participants answered the questionnaire after watching the recorded video and the response rate for the validation was 100%.

3.9 Data analysis

Once the data are collected and checked for errors, they can be used for data analysis. This section describes the data analysis process and methods, which are used in this research.

There are many different data analysis tools with various functionalities such as SPSS, SAS, SYSTAT, STATA, and MINITAB (Kumar, Panwar, Kumar, Shamim, & Mishra, 2018). This research uses SPSS (Statistical Package for Social Science) for the quantitative data analysis and demonstrates the reliability and validity of the research. The collected data were analysed based on their type of measurement (scales, nominal, original) by using quantitative methods. Likert-scale is the most frequently used rating scale method (M. N. K. Saunders, 2019), which is used in this research for the **Cronbach's Alpha** test in SPSS. Cronbach's Alpha is one of the most frequently used method to assess the internal consistency reliability (Gushta & Rupp, 2012). This research used Cronbach's Alpha to measure the consistency of responses to a sub-set of questions (scale items) that are combined as a scale to measure a certain criteria. This method consists of alpha coefficient with a value varies from 0 to 1. Values of 0.7 and above demonstrates an acceptable internal consistency between the responses to the combined questions (Mitchell, 1996; M. N. K. Saunders, 2019).

Thematic analysis is used for the data analysis of response to the interviews. This method is one of the most common methods of qualitative data analysis that involves the search for themes or patterns occurring across a data set (M. N. K. Saunders, 2019). To perform thematic analysis NVIVO is used to code and categorise the data with similar meanings. Coding involves labelling each unit of data with a specific code that identifies different themes (M. N. K. Saunders, 2019).

3.10 Questionnaire Results

This section details the results of the data analysis of response to the online questionnaire. The questionnaire includes quantitative and qualitative questions which are analysed separate.

3.10.1 Quantitative data

Quantitative questions started with demographic questions to have a general knowledge of the background and knowledge of the respondents. Thereafter, the questionnaire started to ask about the existing issues during the structural design process specifically at the early stages. In addition, they were asked to provide suggestions as potential solutions to the existing issues. It was followed by technical questions about the structural design tools, their strength and weaknesses.

3.10.1.1 Demographic information

Respondents were asked to provide information about their highest academic degree, and area of expertise. Figure 21 demonstrates a considerable number of respondents have high academic degree qualifications. According to this figure, 80 respondents have postgraduate levels, 18 of them have undergraduate qualifications, and 6 respondents have some college degrees.

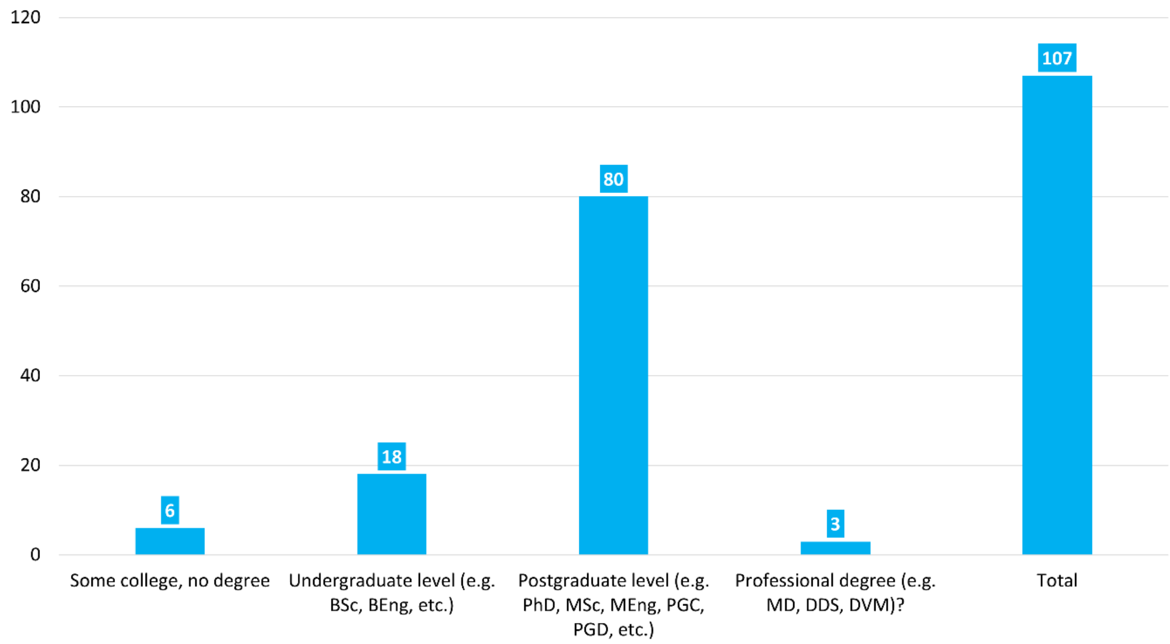


Figure 21: Academic education level of the respondents to the online questionnaire

Figure 22, shows that the majority of the respondents are structural engineers (86), it is followed by architects (11), civil engineers (5) structural design and analysis software technicians (2), project managers (2) and construction engineers (2). Hence, considerable number of the respondents to the online questionnaire are structural engineers.

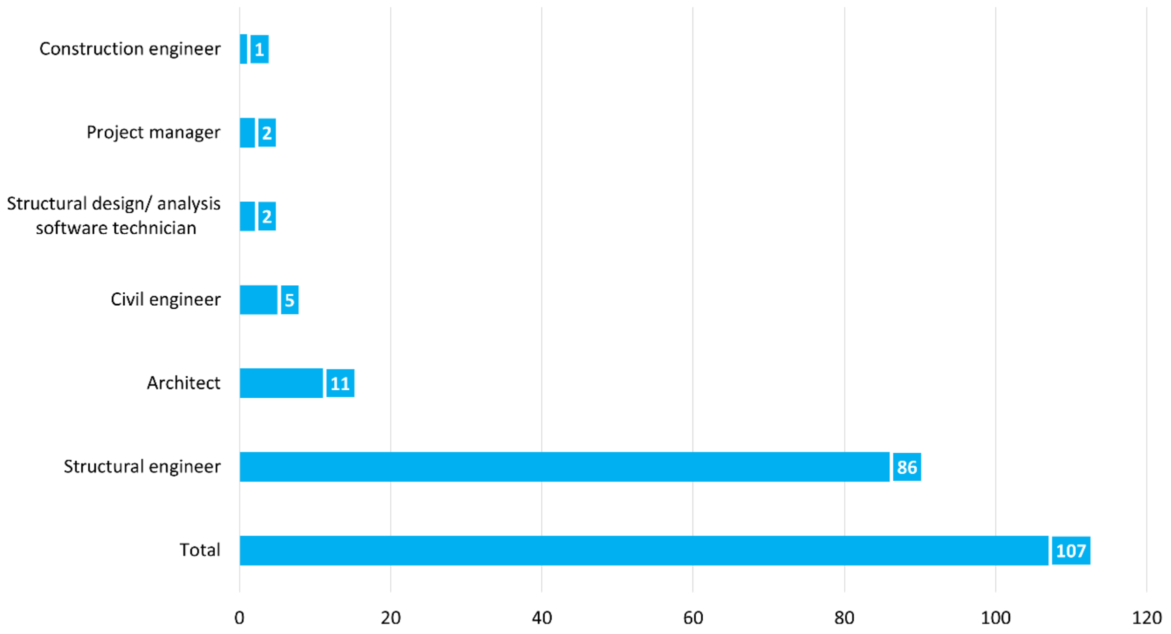


Figure 22: Distribution of the respondents to the online questionnaire in different areas

Figure 23, shows the results of the response to a multiple response question, which asked the respondents about their area of expertise. This question allowed the respondents to select more than one option to provide comprehensive information about the respondents' background. According to this bar chart, residential buildings have the highest rate of response (71), which was followed by high-rise buildings (43), industrial structures (41), bridge (33) and tunnel (10). Therefore, the case study of the proof of concept prototype was automatic structural design of a residential building.

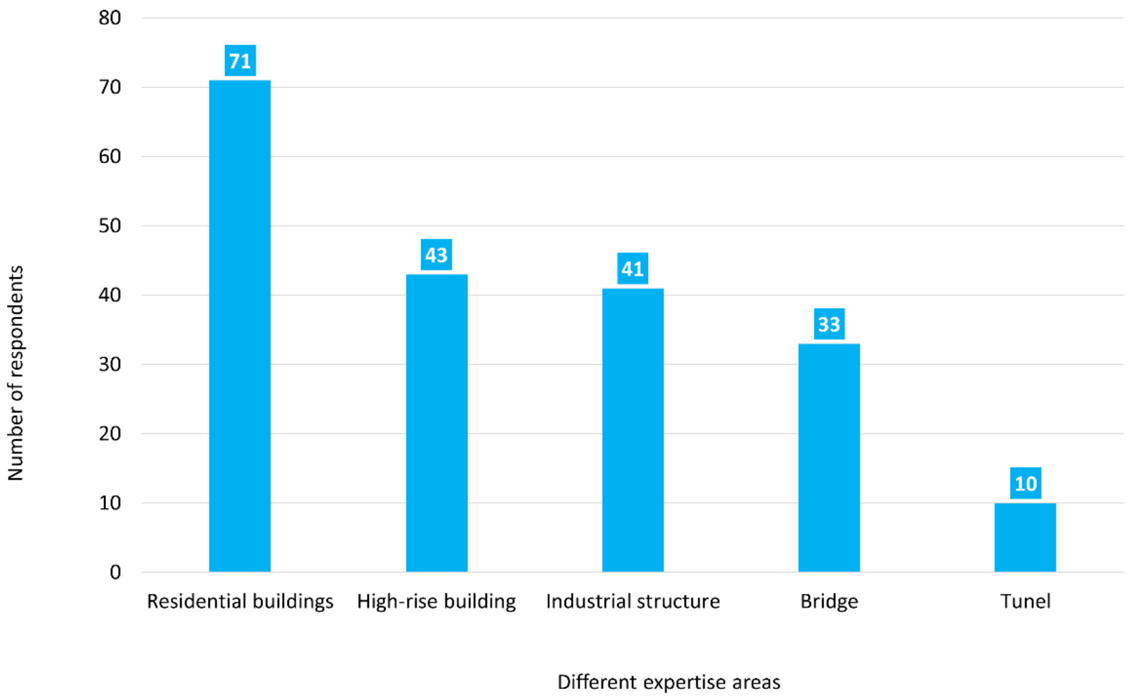


Figure 23: Respondents skills in different areas of civil engineering industry

Figure 24 demonstrates the respondents' distribution in different institutions. According to this figure, the IStructE with 61% of the respondents has the majority of the respondents, which is followed by the ICE (17%) and the ASCE (7%). Moreover, this figure shows that 15% of the respondents are registered in other institutions/ organisations such as European Engineer (EUR ING or FEANI), and there was a Brazilian engineer registered in CREA, Chartered Institution of Highways and Transportation (CHIT) and Member of the Institution of Engineering and Technology (MIET). However, this research focused on the respondents who are members of IStructE, ICE and ASCE.

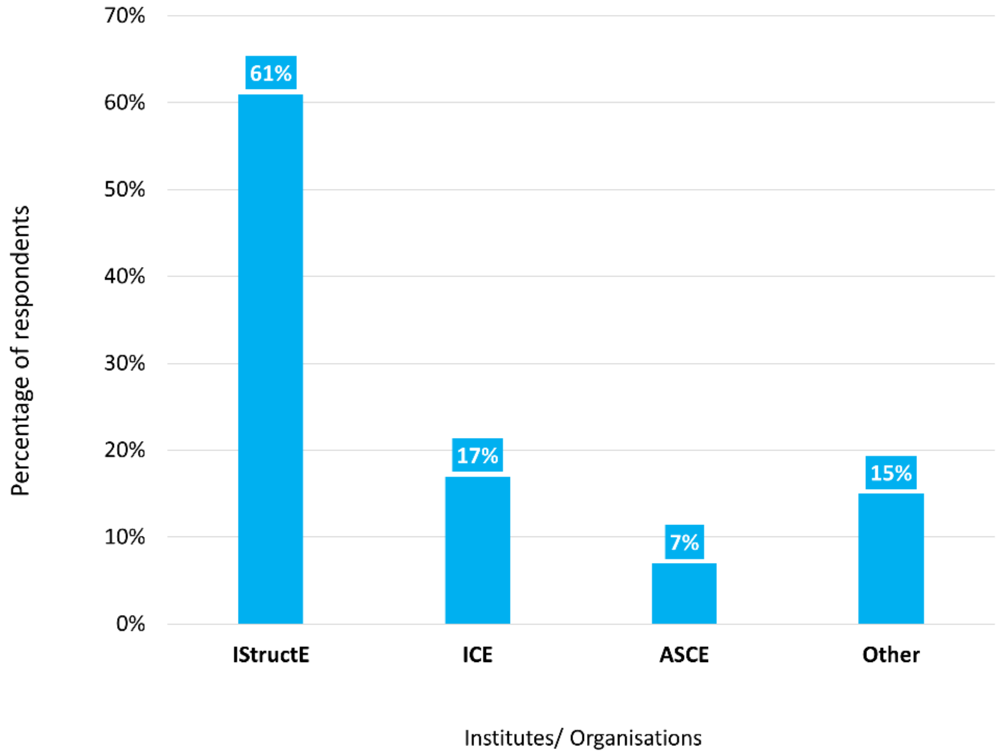


Figure 24: Respondents' distribution in different institutions of IStructE, ICE, ASCE and other institutions.

3.10.1.2 Structural design and analysis

The third part of the questionnaire was dedicated to the questions related to the structural design and analysis process. The first question of this section asked the respondents to rate their level of knowledge of different subjects. Figure 25 shows the results of the responses to this question and in which respondents have a good level of knowledge in Conceptual Structural Design, Detailed Structural Design and Structural Analysis. Although, the results highlighted a lack of knowledge in the Structural Optimisation, Structural Design Automation, Generative and/or Parametric Design and Interoperability with other disciplines.

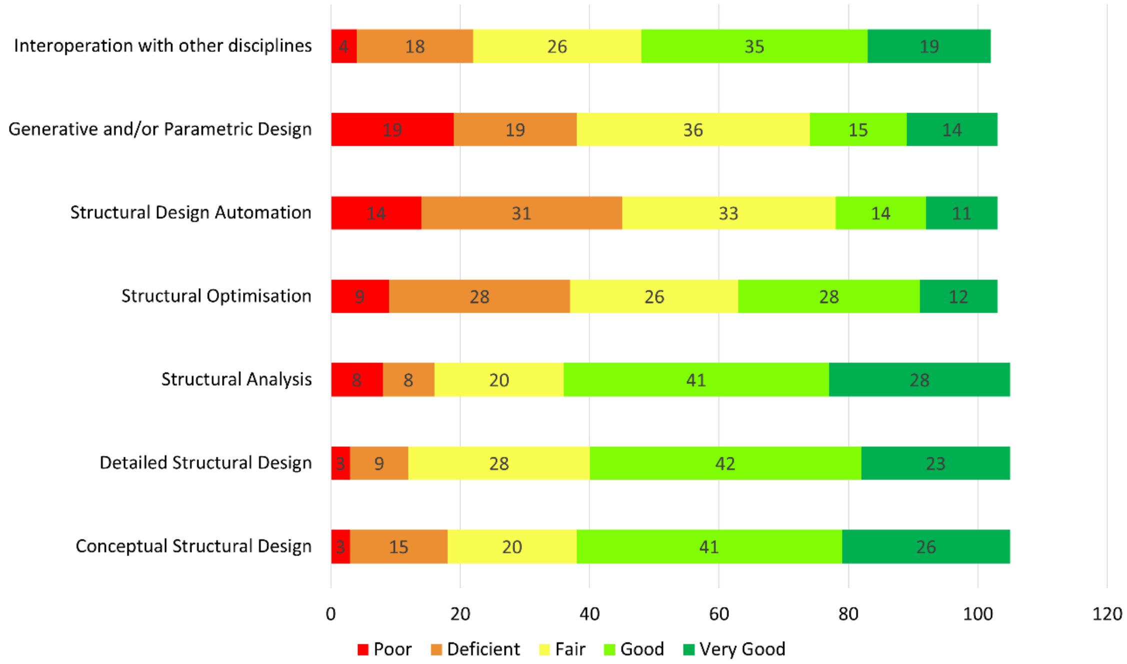


Figure 25: Level of knowledge of the respondents in different areas and tasks

The second question of the structural design and analysis section asked the respondents to select stages, which require more improvements. Figure 26, shows the results of the response to this question. According to this figure, interoperability with other disciplines, structural design automation, structural design optimisation and conceptual structural design require more improvements. This figure contributes to justifying the research knowledge gap and the focus of the framework and proof of concept prototype.

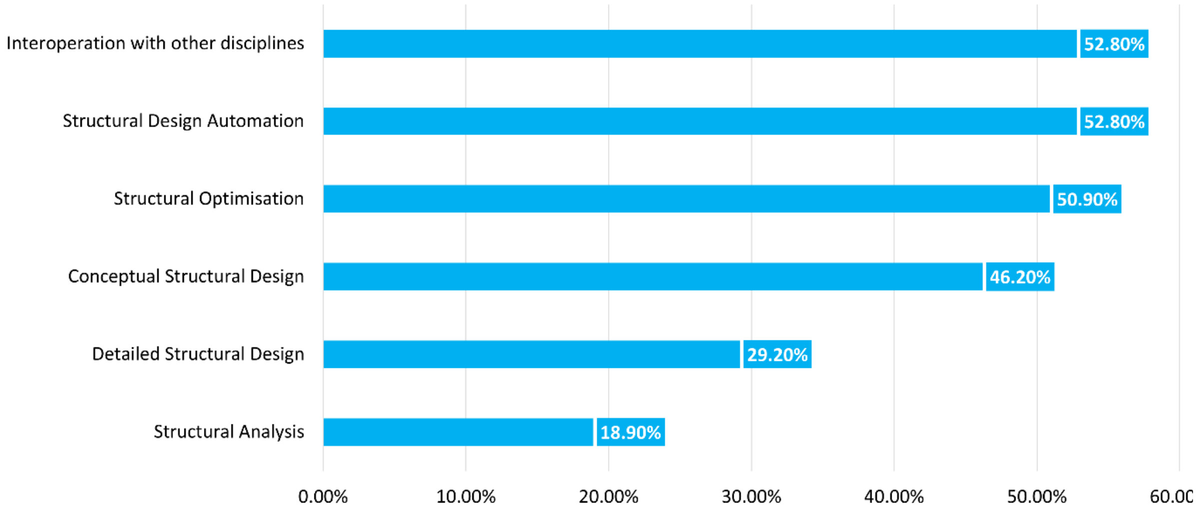


Figure 26: Certain areas that respondents to the questionnaire believe need more improvements

In order to highlight the main focus of the computer tools for the structural design and analysis process, the questionnaire asked the respondents to rate their use of computer tools at each stage of the structural design and analysis process. Figure 27 shows the results of the data analysis of the responses to this question. According to this figure, participants have the highest level of proficiency in the use of computer tools during the analysis of the structural design (50) and the detailed structural design (41) stages. Moreover, this figure indicates that the respondents use computer tools for the conceptual structural design and optimisation of the structural design much less than the detail structural design and analysis of the structural design. This figure highlights the need from the industry to improve the computer tools for the conceptual structural design and optimisation of the structural design.

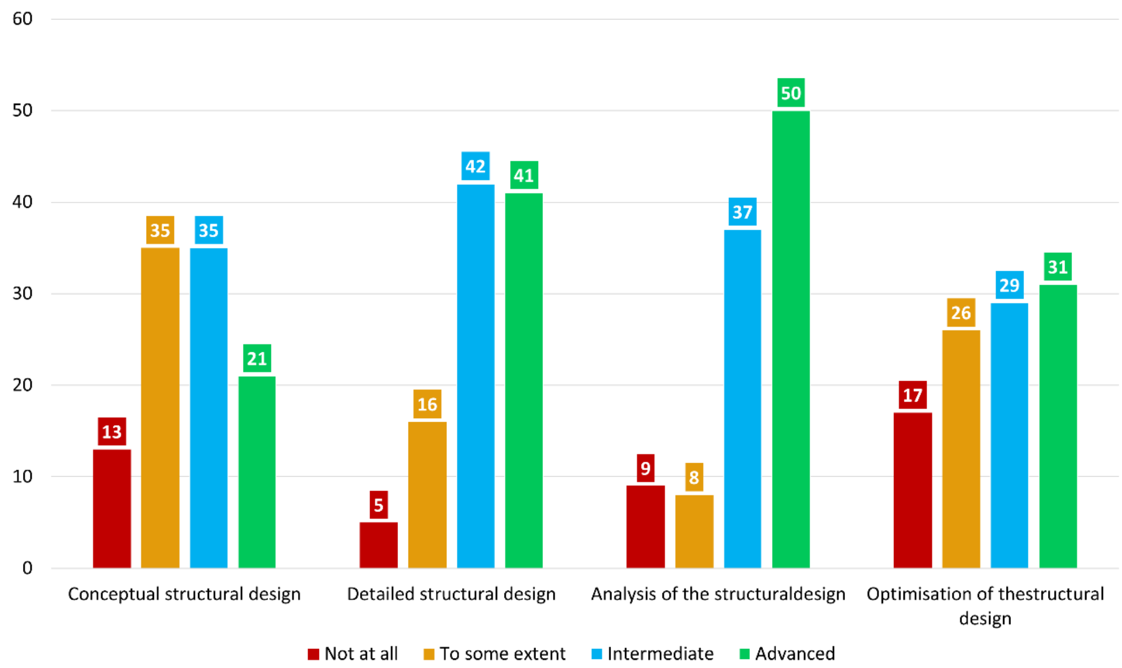


Figure 27: Level of knowledge and skills in the use of computer tools at certain stages of structural design and analysis process

Figure 28 shows the results of a cross sectional analysis of the responses to the two separate questions. The first question asked the respondents to rate their level of proficiency in using computer tools for the structural design and analysis process. The second question asked the respondents to rate how helpful it would be to have a system, which enabled them to generate alternative conceptual structural models, which helps to choose the best model between alternatives. In this chart, the value of 1 on the horizontal axis represents the minimum value and the value of 5 represents the maximum value. This bar chart demonstrates a similar trend for the responses to the both questions. In this scenario, people with less skill in using computer tools for structural design thought that generating alternative models at the early stage of structural designs is not an important task. While respondents with more experience and skill in using computer tools for the structural design believed that this is very important and helpful to have a system, which helps to generate alternative structural models at the early stage of structural design process. In other words, the more experience and skill the respondents have, the more they believed that generating alternative structural models at the early stage of structural design would help the designers and engineers.

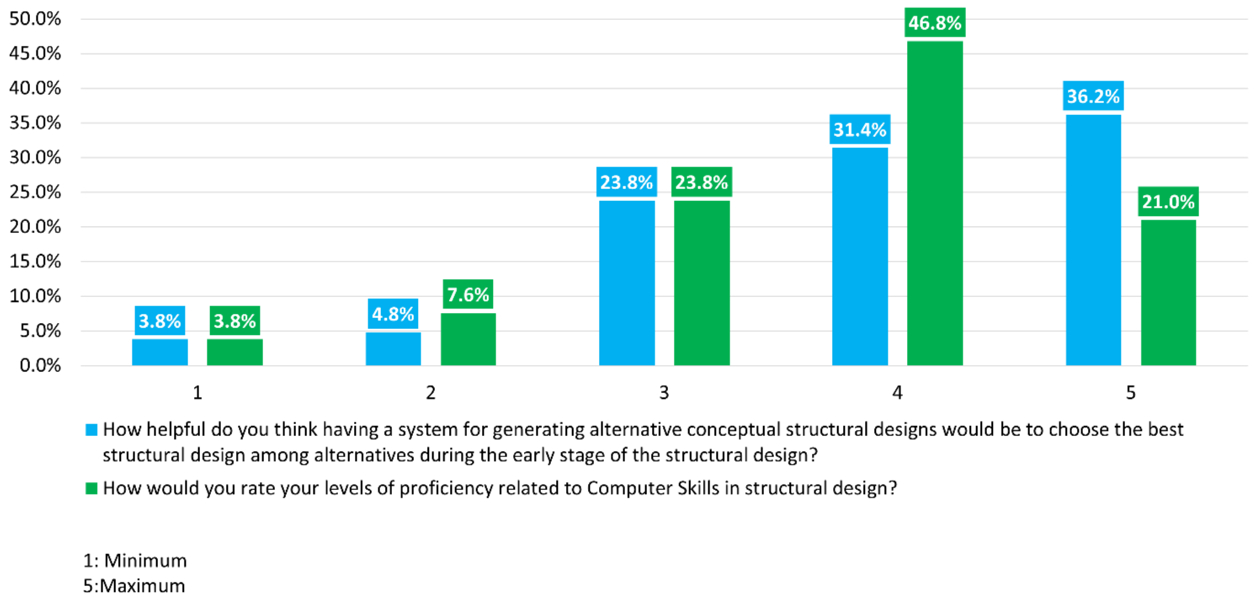


Figure 28: Cross sectional analysis of two separate questions to evaluate the importance of the proposed framework to the respondents with different level of experience.

After justifing the knowledge gap and highlighting the need of the structural engineers to have a framework which improves the integration between the architectural models and the structural models and facilitates the structural design process through an automatic process, the questionnaire explored the most suitable platform to implement the proof of concept prototype. In this scenario, the respondents were asked to identify the structural design tools based on their level of use and proficiency. Figure 29 demonstrates the results of the responses data analysis in SPSS. According to this figure, Revit, ETABS, Sap 2000, Robot, Tekla and STAAD Pro have the highest level of usability in the current industry. Further questions were used to gather comprehensive information about the existing tools and to decide on the potential tools to develop the prototype. In this scenario, the respondents were asked to identify on the provided list, the structural design and analysis tools based on their usability. Figure 30, shows the results of the data analysis of the responses to this question. Green arrows in the figure indicate the tools with the highest response rate. According to this figure, Sap 2000 and Robot were reported as having the highest use for the structural analysis process. ETABS and Robot were reported as the tools with the highest use for the structural optimisation process and Revit was reported as the most practical tool for the conceptual structural design. However, this research is based on the BIM platform and aims to improve the collaboration and interoperability between architectural and structural models. Therefore, two more criteria needed to be considered during the tool selection for the prototype development; efficient performance in BIM platform, and a strong link with Revit and Dynamo to perform a smooth integration with architectural models from Revit and enable automatic dsign performance in Dynamo. Therefore, a combination of Revit, Robot and Dynamo were decided to be used for the prototype development.

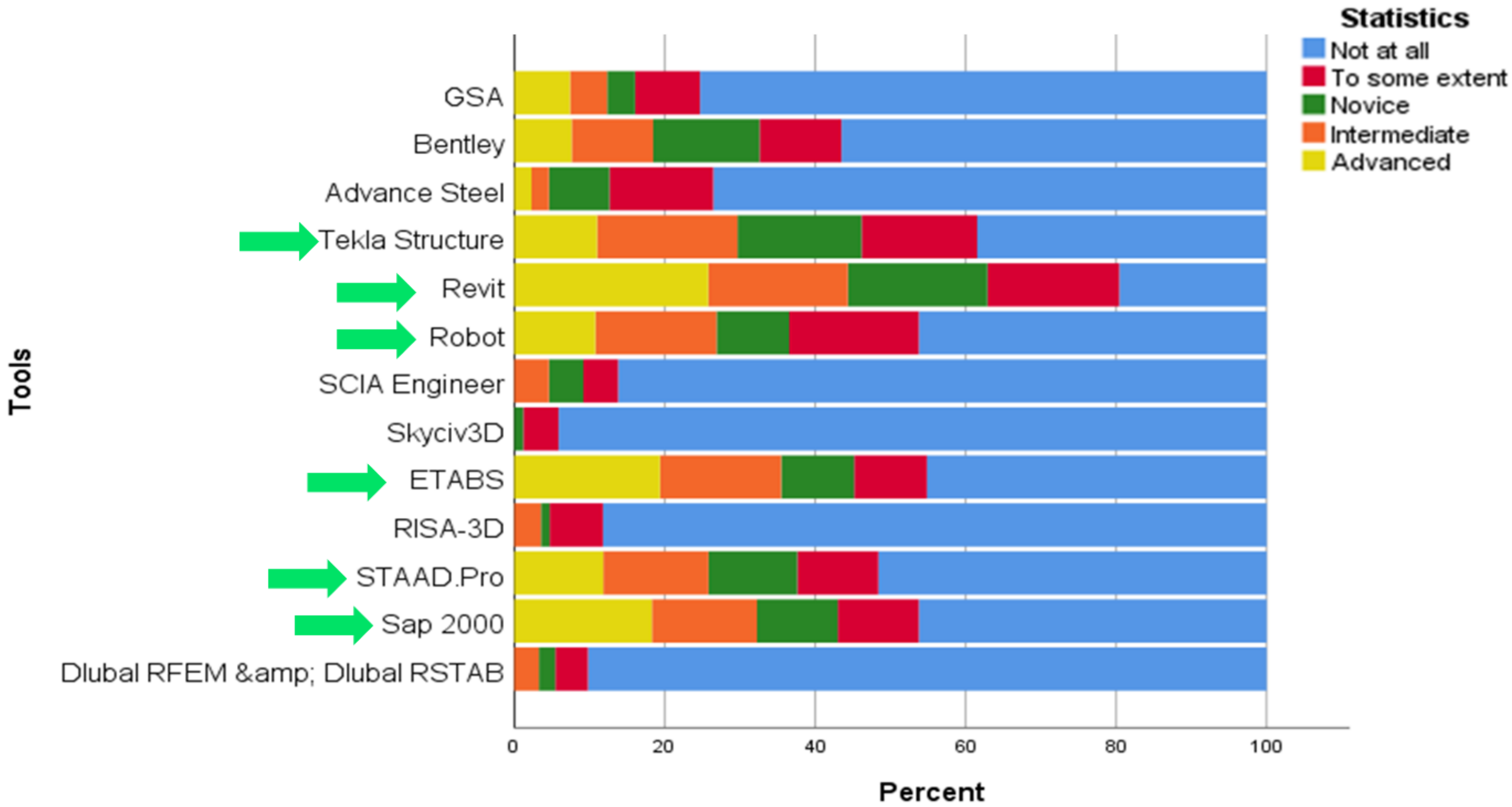


Figure 29: Identification of tools based on the knowledge of the respondents and level of use. Green arrows indicate the tools that respondents have more knowledge and experience to use.

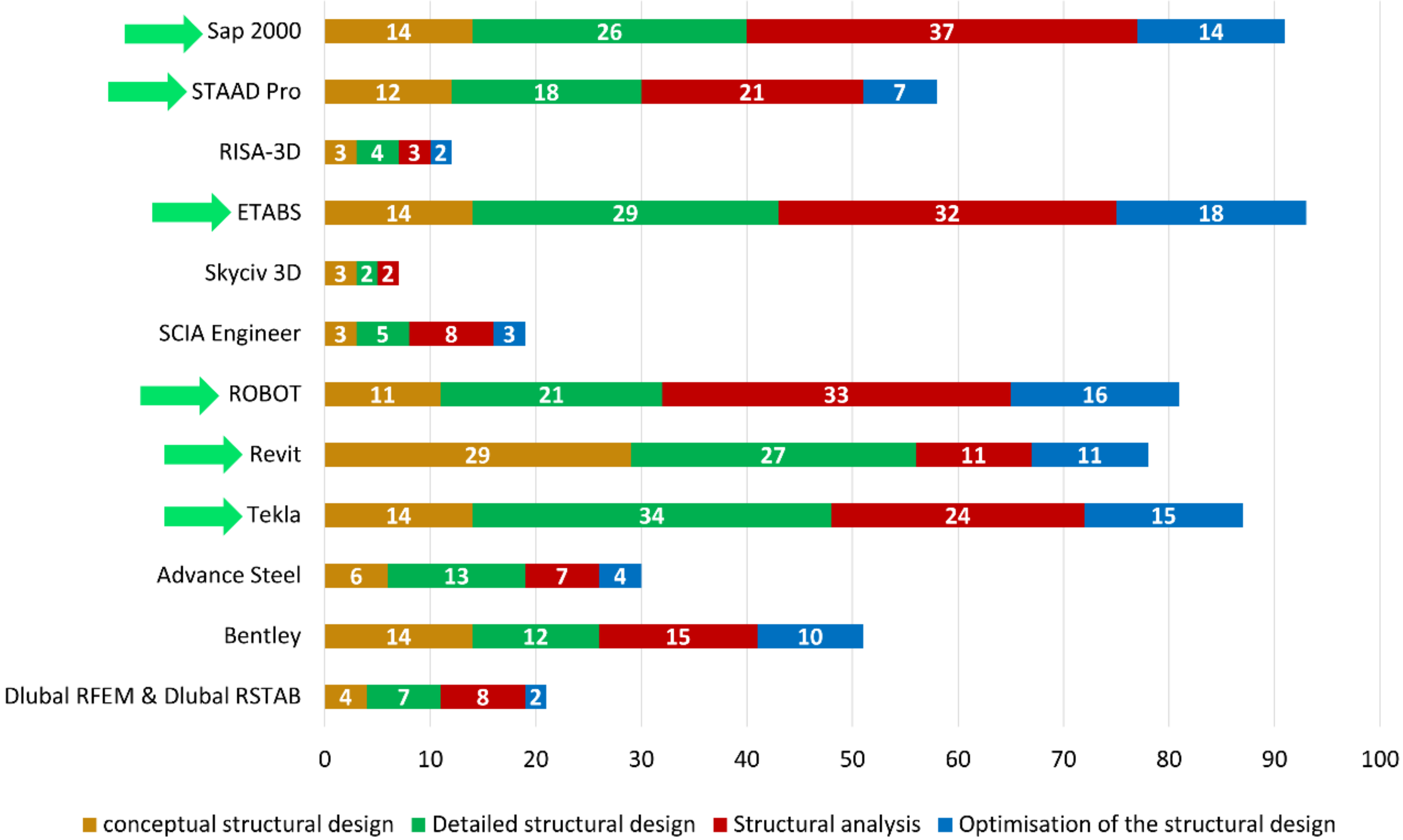


Figure 30: Identification of tools based on their usability. Green arrows indicate the tools that have more advantages to be used in the prototype.

3.10.1.3 Building Information Modelling (BIM)

This research is based on the BIM platform; hence, the third section of the questionnaire is dedicated to BIM. Therefore, this section begins with a question asking the respondents to identify their level of awareness and skills proficiency in BIM tools (Figure 31). According to the figure 31, 17.7% of the respondents are experts in BIM, 41.9% are aware of BIM and currently use it in their projects, 33.3% of the respondents are aware of BIM but do not use it and only 7.6% of the respondents do not have knowledge and skills in BIM (their responses were excluded in questions about BIM).

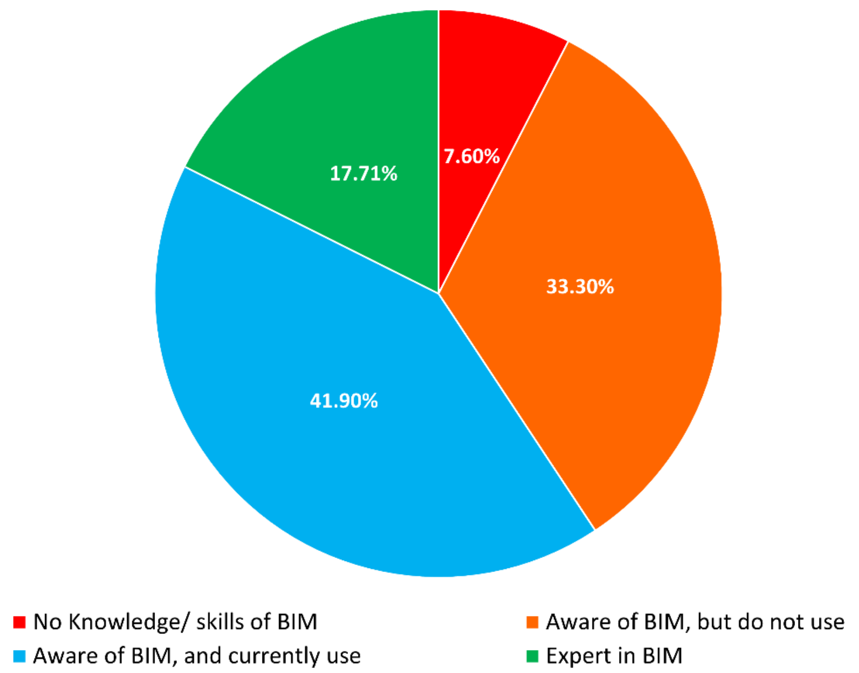


Figure 31: Level of awareness of the respondents of BIM

Following the question about the level of awareness in BIM, the questionnaire asked the respondents to rate how BIM supports the early stage of the structural design (figure 32). According to figure 32, data analysis shows that 15% of the respondents believe that BIM is lacking in supporting the early stages of the structural design and 41% of the respondents believe that BIM supports the early stage of the structural design to some extent. Furthermore, this figure shows that 22% are not sure about the capability of BIM at the early stage and only 21% believe that BIM supports all the aspects of the early stages. According to figure 31, almost 75% of the respondents are BIM users and experts in this area. On the other hand, figure 32 highlighted that 78% of the respondents believe that BIM lacks to support all the aspects of the early stage. This comparison highlights the fact that BIM requires further development at the early stage of structural design.

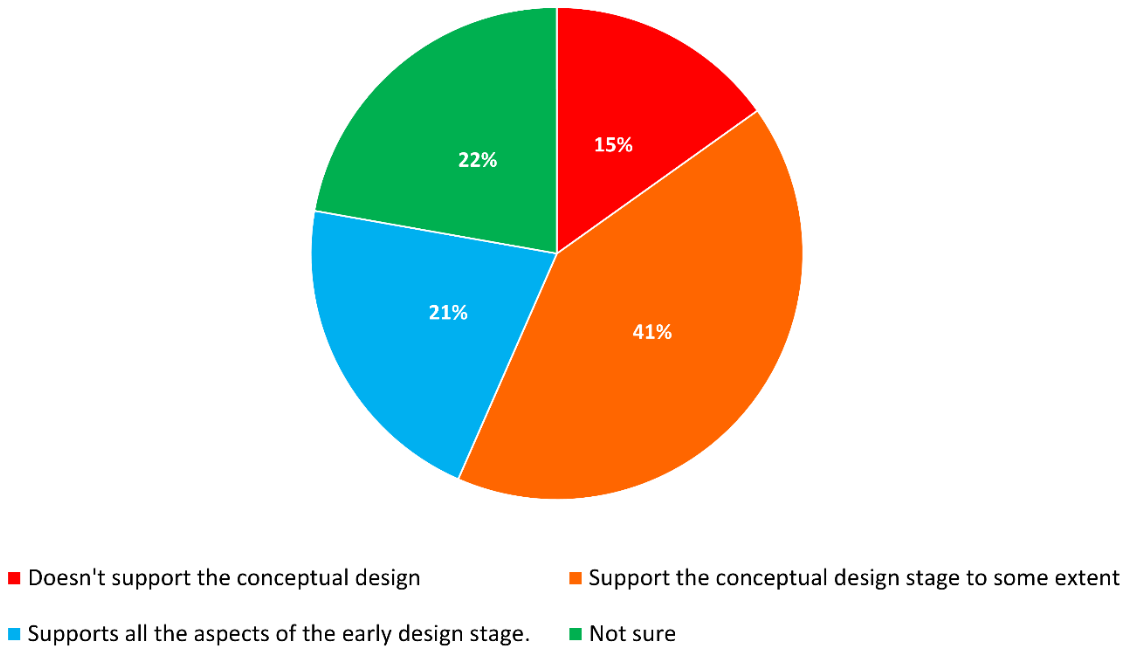


Figure 32: How BIM supports the early stages of the structural design process

3.10.1.4 Generative Design (GD)

The questionnaire narrowed down the questions in more detail about adopting automation in the structural design process. Therefore, the questionnaire asked the respondents whether automation in the structural design and analysis could improve the designers' capabilities during the early stages. In response to this question 61.3% of the respondents answered 'Yes', 32.1% of the respondents answered 'Maybe' and only 6.6% of the respondents answered 'No' (Figure 33). This question was followed by another question asking the respondents whether a combination of automation and BIM technology could improve the designers' capabilities during the early stages. Data analysis showed that 69.3% of the respondents answered 'Yes', 26.7% of the respondents answered 'Maybe' and 4.0% of the respondents answered 'No'. Comparison between data analysis of the responses to these two questions indicates that combination of automation and BIM technology would be a suitable platform to improve early stages of the structural design process.

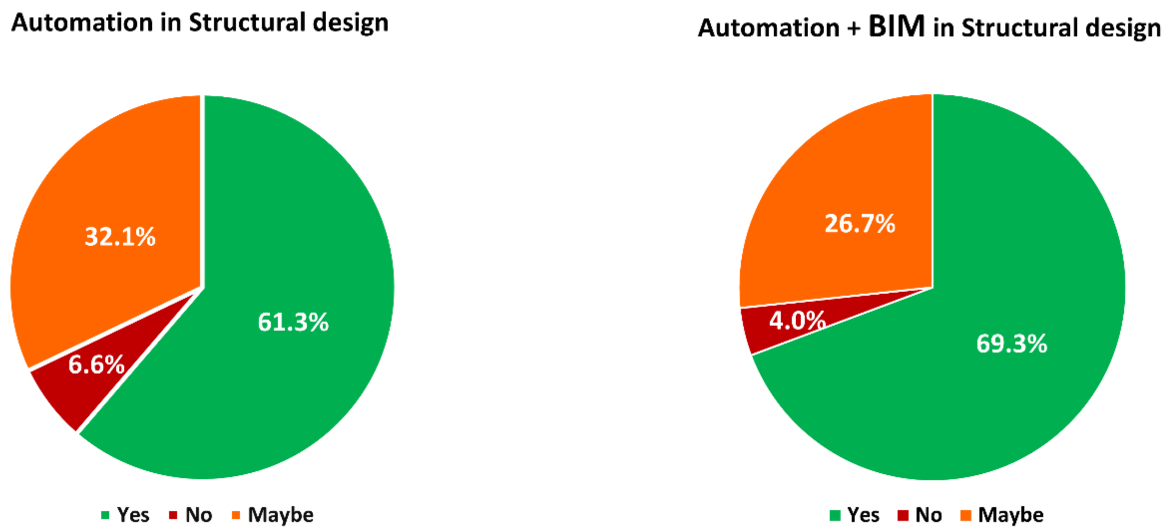


Figure 33: Respondents rate to the question whether automation in structural design would be helpful or not

The second and third questions in this section narrowed down the questionnaire in more detail about GD and using GD in BIM. It was expected that the level of awareness of GD would be limited especially in industry. Therefore, during the questionnaire design and development, one question was dedicated to the GD knowledge of the respondents. Interestingly, the results of the respondents confirmed the expectation and indicated that 40.2 % of the respondents are not aware of GD. Therefore, a cross sectional data analysis was performed on the results of responses to two separate questions, and to classify the responses based on the respondents' knowledge of GD. The first question asked the respondents to identify their level of awareness of GD, and the second question asked the respondents whether integration of GD and BIM at the early stage of the structural design could improve designers' capabilities. Figure 34 indicates the results of the cross-sectional data analysis of these two questions. This figure indicates a relationship between the level of skills/knowledge in GD and the response to the second question asking whether GD in BIM could improve the capability of the structural engineers. In this scenario, the majority of the respondents believe that GD in BIM will improve the capabilities of the structural engineers during the early stage of structural design.

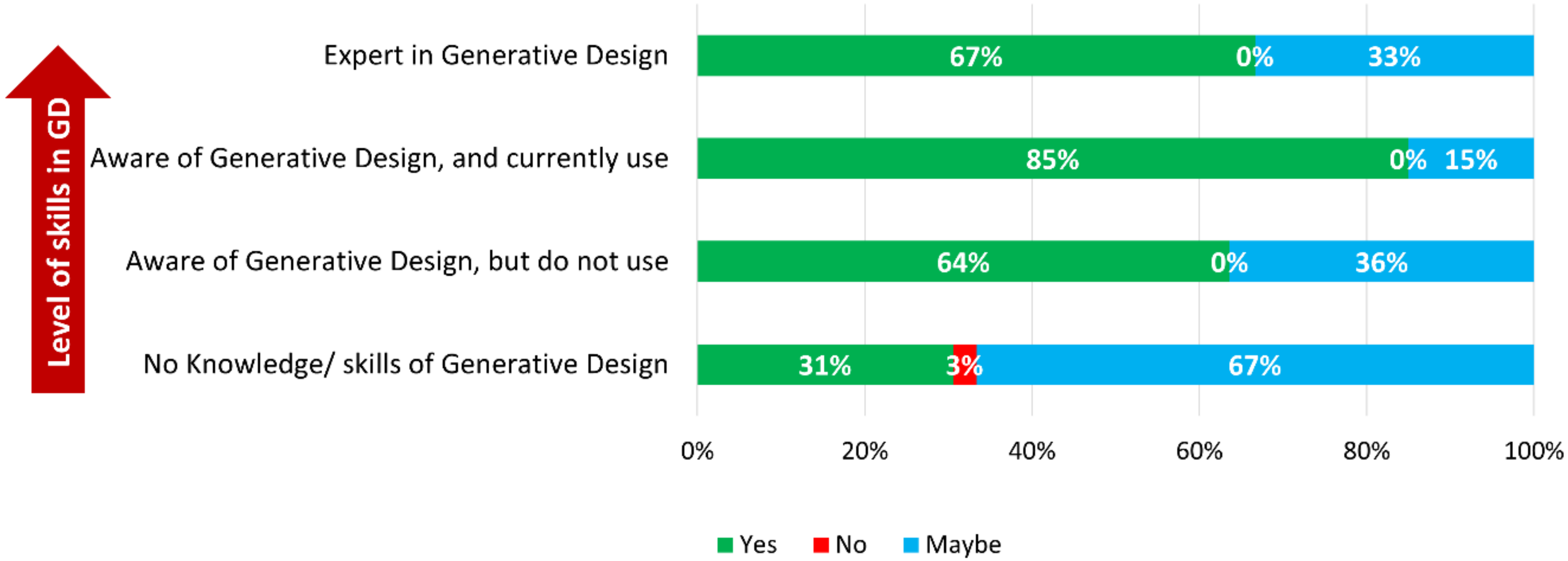


Figure 34: results of the cross sectional data analysis of level of skills in GD and response to the question whether GD in BIM could improve the capability of the structural engineers

3.10.2 Qualitative data

This section describes the results of the qualitative data analysis. This questionnaire includes four qualitative questions, which are used to achieve more information from the respondents. These questions begin with asking about the current issue(s) during the structural design process. It was followed by other questions asking whether they are aware of any potential solution(s) to solve the issue(s). Furthermore, respondents were asked about the method they use to consider alternative structural models during the early stages. The following subsections describe the results of the qualitative data analysis, which was performed in NVIVO and EXCEL.

3.10.2.1 Current issues

The first qualitative question asked the respondents to list any specific problem(s) during the structural design and analysis process. Qualitative data analysis in NVIVO indicated that 50 of 107 participants responded to this question. Word frequency of all the responses were performed in NVIVO to find the most frequent words in regards to the first question (figure 35).

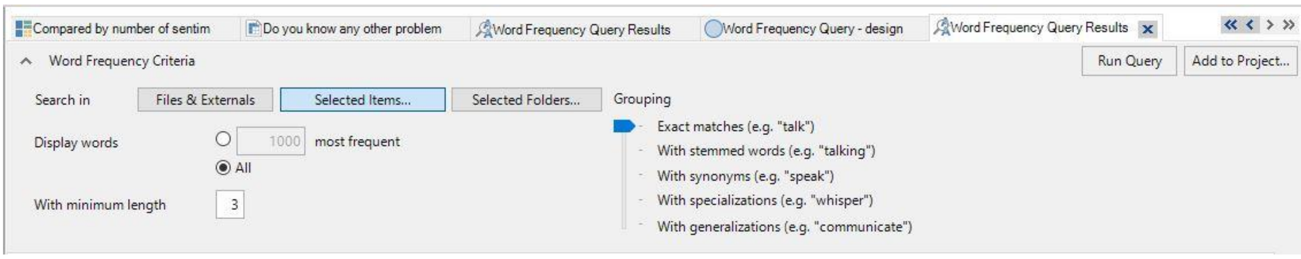


Figure 35: word frequency in NVIVO for 50 responses to the first question about the current challenges during the structural design and analysis process.

Figure 36 shows the word frequency results of the response to the first question about the current issues during the structural design. According to this figure “time”, “automation”, “optimisation”, “concept”, “conceptual”, and “process” are the most frequently used words in responses to the first question. This highlights the fact that time consuming processes are the main concern of the structural engineers. In addition, automation and optimisation are the potential solution to reduce iterative design processes at the conceptual stage.

Figure 36: Word cloud of the word frequency results of the response to the first qualitative question about the current issues during the structural design analysis process.

Thematic analysis was performed on the responses to the first question by using NVIVO 12 to highlight the main issues in the structural design and analysis process. In total, 43 responses were coded in 5 different themes including; conceptual design (11), interoperability and collaboration (10), knowledge and experiences (9), optimisation (8) and state of the art technology (5) (figure 37). This figure indicates that the majority of the respondents believe that there are issues at the conceptual stages of the structural design.

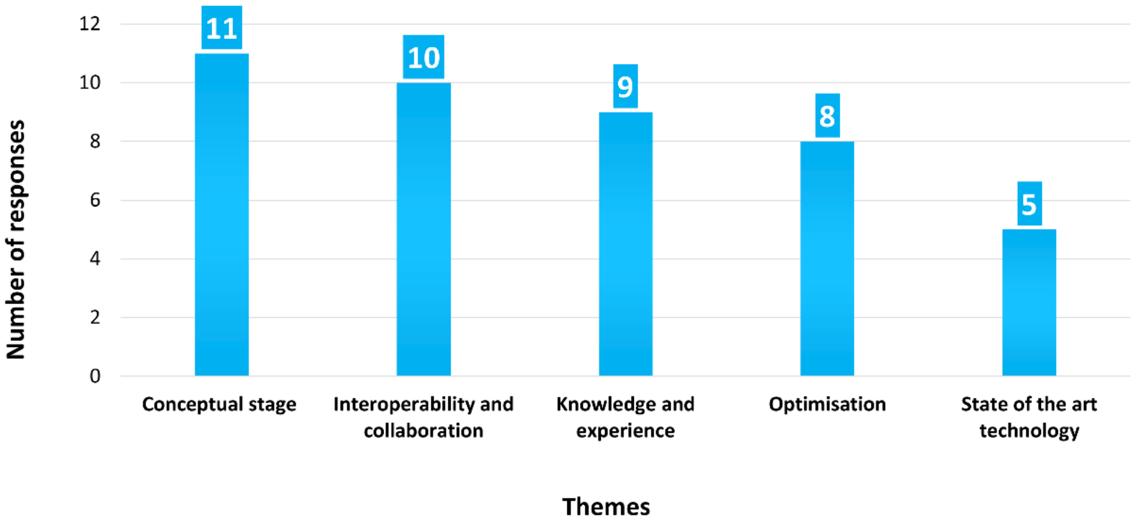


Figure 37: Thematic analysis of the response to the first question about the current issues during the structural design process.

Content analysis was performed on the results of the thematic analysis to achieve more information about the current issues during the structural design processes and to provide a suitable framework and proof of concept prototype to solve the issues. “Conceptual stages” was the highest issue reported by the respondents to the questionnaire. Content analysis of the conceptual stage node indicated that respondents believe that the conceptual stage lacks in speed and requires fluent performance. Furthermore, they argued that a practical design analysis at the later stages is unable to replace flaws in the concepts. Several respondents reported that most of the time, the design changes in one discipline (such as architecture) pause the design process in other disciplines (such as structure) and reduces the time for the structural engineers to make changes. They believe that conceptual design requires more coordination between architects, structural and civil engineers to avoid the design change at the later stages. Several respondents believe that conceptual design takes a lot of time to finalise and after finalising the concept, during detail design, they have many clashes with architects and have to think of something new. Several respondents believe that general involvement of the engineer from conceptual stage is limited, which can lead to difficulty during the later stages.

Interoperability and collaboration is the second highest issue, which is highlighted during thematic analysis. Several respondents believe that many architects are adopting BIM technology and it is difficult to work with them in terms of collaboration, communication and interoperability. Many respondents asserted that sometimes they spend a lot of time amending and changing designs, which can be difficult, particularly at the end of the process, and often occurs because other disciplines and contractor/supplier designs are developed out-of-sync with structural designs and it is difficult to persuade other disciplines to make changes when necessary. Moreover, many respondents believe that architects consume more time in finalising the initial sketches particularly for complex and very large development projects while structural engineers are pushed to complete the concept design in a short period. Several respondents believe that interoperability between design and analysis packages is still lacking and generally, only the first pass is reasonable (it lacks a back and forth process).

Knowledge and experience is the third highlighted issue in the thematic analysis. A number of respondents believe that project related expertise, experience and fundamental knowledge of the structural design is an important issue. Furthermore, several respondents reported the lack of skills in automation, optimisation and supervision of computer run models.

Optimisation is another area, which is lacking during the structural design process. In this regard, respondents believe that structural engineers opt for structural element sizes, which are overdesigned. They believe that optimisation of a chosen structural design should be straightforward, but tends not to be. The creative and difficult part is to choose a solution to take forward to the detailed design. They believe that current structural design processes consume too much time on repetitive calculations, which result in overdesigned structures with lots of discrepancies and mistakes in hand calculations and estimations.

A lack of creativity and using new technologies and automation is the final issue, which is coded as state-of-the-art technology. In this case, the majority of the respondents reported a lack of new methods to facilitate the structural design process in an automatic manner. They believe that the BIM process is often absent in small organisations that do structural and architectural design. This leads to delays in the timing and optimisation of the facilities that one might have by having a 3D and 4D view of the project. Several of the respondents believe that BIM and automation can provide quality assurance especially in complex designs.

3.10.2.2 Suggested solutions

After asking the respondents about the existing issues during the structural design and analysis process, they were asked to suggest potential solutions to solve the issues. From 107 participants in the questionnaire, 47 participants responded to this question. Word frequency was performed on the whole responses to this question in NVIVO 12. The results of the word frequency indicates that BIM and automation has the highest number of occurrence amongst responses to the second qualitative question (figure 38).

Figure 38: Word cloud of the word frequency results of the response to the second qualitative question about the potential solutions to solve the current issues during the structural design and analysis process.

Similar to the first question data analysis, thematic analysis was performed on the responses to the second question to highlight the main potential solution(s) suggested by the respondents. Figure 39 shows that using automation with 23 responses has the highest rate of response, which is followed by providing training and use of BIM technology with respectively 12 and d 5 responses.

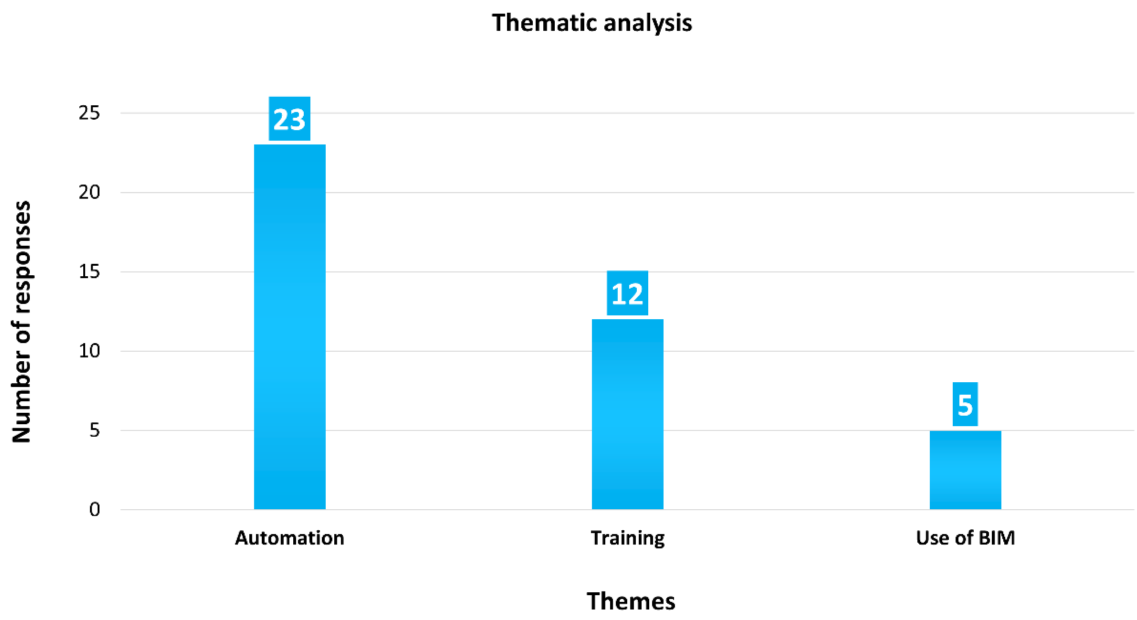


Figure 39: Thematic analysis of the response to the second question about the suggested potential solutions to solve the current issues during the structural design process.

Content analysis of the responses to the second question indicates that majority of the respondents believe that automation is the potential solution to the existing problems and it should facilitate the engineer to make good choices especially at the early stages. They argued that automation at the conceptual design stage could always provide the basis for better outcome. They believe that choosing the best conceptual design should rely on detailed data and may occasionally need preliminary calculations to avoid major changes throughout design process. Several respondents believe that adopting automation in the BIM platform could improve the collaboration and interoperability between different disciplines from the early stages. Other respondents stated that automation helps to explore creativity without limits. They believe that automation could be used for complex optimisation and to assure the quality of the optimum model.

Several respondents expressed the need for a new optimisation software, which provides an economic solution rather than just analysing a proposed solution. They believe that current AEC industry needs to use data science, machine learning, and uncertainty principles to improve design software's optimisation methods with other available successfully optimised structures. Other respondents suggested developing a system capable of creating object based modelling which helps to create conceptual FEM model based on the Revit or Tekla model. However, several respondents believe that automation without supervision brings out wrong data. Therefore, they suggested developing systems to prove the effectiveness and to work with reviewers to ensure designs produced with automation are valid. In this case, many respondents suggested using new visual programming tools such as Dynamo and Rhino in the structural design and analysis processes. A few respondents asserted that there are multiple programs with the capability of automatic design but very few of them interact in the current tools. Therefore, after the automatic performance, engineers need to remodel the design and then draw it in BIM. Thus, a considerable number of respondents suggested providing regular training and improving the knowledge about new technology such as automation and BIM. Data analysis highlighted that after automation, education and training is the highest suggested solution for the current issues during the structural design and analysis problems. They believe that developers need to understand the requirements of designers. The majority of the respondents stated that all design studies need to raise awareness about structural and architectural BIM design. In addition, the BIM level 2 design is not sufficient to ensure the optimisation of the process, therefore a great effort must be made to reach shared software platforms where all the stakeholders can easily see the different aspects of the project (Architectural-Structural- MEP-Landscape), offering the possibility to have a real time optimisation without loss of time and money. They believe that having a balanced and well-structured organisation helps to raise the awareness of the qualified personnel in this area to provide training and to break down the problem into smaller problems. Finally, many respondents asserted that use of BIM helps to integrate the different disciplines and increase collaboration and schedule detailed coordination.

3.10.2.3 Generation of alternatives

The last qualitative question of the questionnaire is about considering alternative structural models at the early stages. This question asked the respondents how they generate alternative structural models at the early stages. From 107 participants in the questionnaire 59 participants responded to this question. The results of the word frequency indicates that experience and parametric modelling are the most frequent words used in response to this question (figure 40).

Figure 40: Word cloud of the word frequency results of the response to the third qualitative question about considering alternative structural models at the early stages

Thematic analysis of responses to the third question indicates that majority of the respondents generate alternative structural models using trial-and-error methods based on their experience. Moreover, 6 respondents said that they use automation and 2 respondents use brainstorming for this purpose (Figure 41).

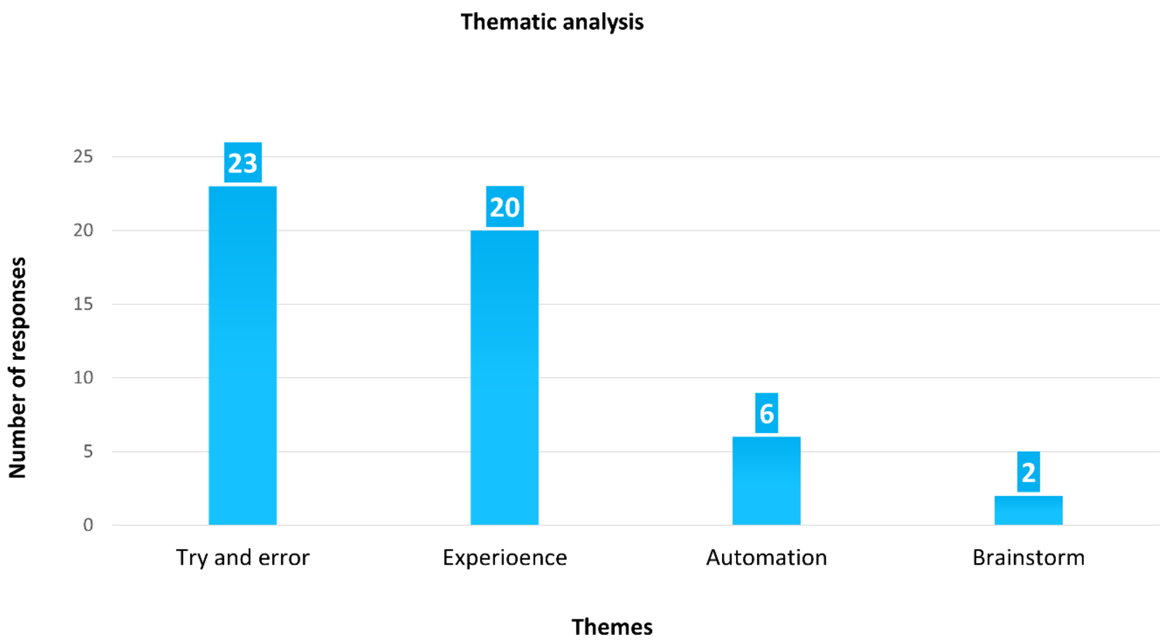


Figure 41: Thematic analysis of the response to the third question about considering alternative structural models at the early stages

Content analysis of the response to the third qualitative question indicates that the majority of the respondents produce the initial sketch of the model and try to improve it using the trial and error method by considering the various materials available for the construction (RC, Steel etc.), section sizes and site access. Furthermore, basic engineering principles and design guides plays a key role in providing an estimate of the structural sizes. In this process, structural engineers use the architectural drawings or models to overlay structural frames. Therefore, any change in the architectural models requires remodelling and recalculation of the generated structural model. The majority of the respondents believe that this iterative and time-consuming process prevents them from considering alternative models. Therefore, they tend to design according to previous similar projects or other successful projects.

3.11 Interviews results

The results from the interviews showed that majority of the participants stated that this research is proposing a valuable idea and the prototype includes the potential of further development for commercial use. One of the chartered structural engineers in IStructE stated; “I think it is really good and it is definitely something we are exploring and we do need in the future and linking the software together. So it’s a really useful process and at the right time as well.” Other respondent said: “I thinks it’s a really interesting work that in the current situation in revolution of digitalization, this system accelerate the business and facilitate our work. This is one of the main requirements of the current market”. They stated that converting the architectural model to different alternative structural models and analyse them is an interesting part of the prototype. They also mentioned that; “the option to perform optioning, the sliders to change the number of design variables automatically and get quickly the forces at the elements are very practical and that is sometimes very helpful when you are trying to come up with a scheme”. One of the responses said: “The idea of making most economic design is very interesting as its more targeted request from client”. They argued that this prototype is capable to help the current market in terms of saving time and cost. However, this prototype needs further development as buildings are becoming more complex. Participants believe that the prototype follow a logical order for structural design process. One of the charted structural engineers in response to the question “Do you think the prototype/framework follow a logical order?” said; “I think so, that is a sort of process I would do to look at the architectural model, decide where to put the columns and beams and apply loads”. Most of the participants believed that the proposed prototype is useful at the early stage structural design and decision-making process. One of the chartered structural engineers in response to the question “Do you think we can use it for decision making at early stage to select the best design?” answered: “yes, especially when it allows you to create different framing options and allows you to adjust it. It definitely helps to come up with quick schemes that help to have a better design because in reality you never have an ideal optimum design there is always a compromise somewhere”. Interestingly, all the respondents showed interest in learning the prototype and one of the chartered structural engineers said: “it is something definitely I want to learn and in my lectures I recommend it to the university that automatic deign is something needs to be added to the curriculum. I do not think anyone would say I do not want to use it because it is something, which makes the life easy. The only think I can think of is the prototype not being able to cope with big and complex geometries, which we have, in the reality. This system definitely create positive impact in structural design process and WSP currently spending on automation design quite a lot. This prototype is coming up with different schemes but sometimes the most challenging aspect is the coordination and the design development. If it could be adapted to that point and the technology catches up it would be really good tool”. This interview also provided great advises for further development and future work. One of the chartered structural engineers said: “You are working on the early stages, the other part which is really frustrating for the structural engineers is when the design finished and start to producing the calculations packs to send to building control to approve it which is very time consuming and sometimes it takes months”.

Results of the focus group showed that almost all of the participants believe that the proposed prototype is capable to address a very current need. It was also reported that combination of integration between architectural design and structural design and optimisation process is a very interesting part of the research. Majority of the respondents were interested in the automatic integration of several existing tools using visual programming. They believed that this process makes it more accessible than coding-based solutions. They also stated that the prototype follows a logical order and it is capable to facilitate the structural design process. However, it was also raised that optimisation process requires more development. They stated that at the early stage, cost optimisation is another potential solution to compare alternative models and make a better decision on the optimal solution. They also suggested to implement more variety in objectives, constraints, materials and structural systems for the future work.

3.12 Research validity and reliability

According to Creswell & Plano Clark (2017) it is important to have a sound research methodology for every undertaking that has been made during data collection, data analysis and interpretation. Therefore, from the beginning of the questionnaire design stage to the data collection and data analysis stage, different measurements were used to ensure the data validity and reliability. This research ensured the content validity of the questionnaire through an extensive literature review and pilot study. As well as validity, it is crucial to consider the reliability of the research. Reliability refers to replication and consistency (M. N. K. Saunders, 2019) and is about the research methodology being consistent in various circumstances so the results are consistent (Creswell & Creswell, 2018). Mitchell (1996) stated three methods to assess the reliability of a research:

- Test re-test refers to conducting the same test over time
- Internal consistency refers to the connection between responses to the questions of the questionnaire
- Alternative forms refers to comparing responses to equivalent forms of the same question

In this research test re-test was not utilised, as the questionnaire would have needed to be sent and completed twice by the potential respondents, which may cause practical problems, as it is difficult to convince respondents to answer the same questions twice. In addition, the alternative form reliability test was not adopted in this research, since the respondents may suffer from fatigue owing to answering a long questionnaire and they may spot equivalent questions and repeat the answer to the previous questions. Therefore, in order to tackle the problem, the positions of the potential respondents were identified to ensure the data reliability. Figure 42, demonstrates that respondents had a great level of experience in their skill area. Moreover, this figure demonstrates the diversity of the respondents from different institutions, which represents evidence of reliability related to the data sources.

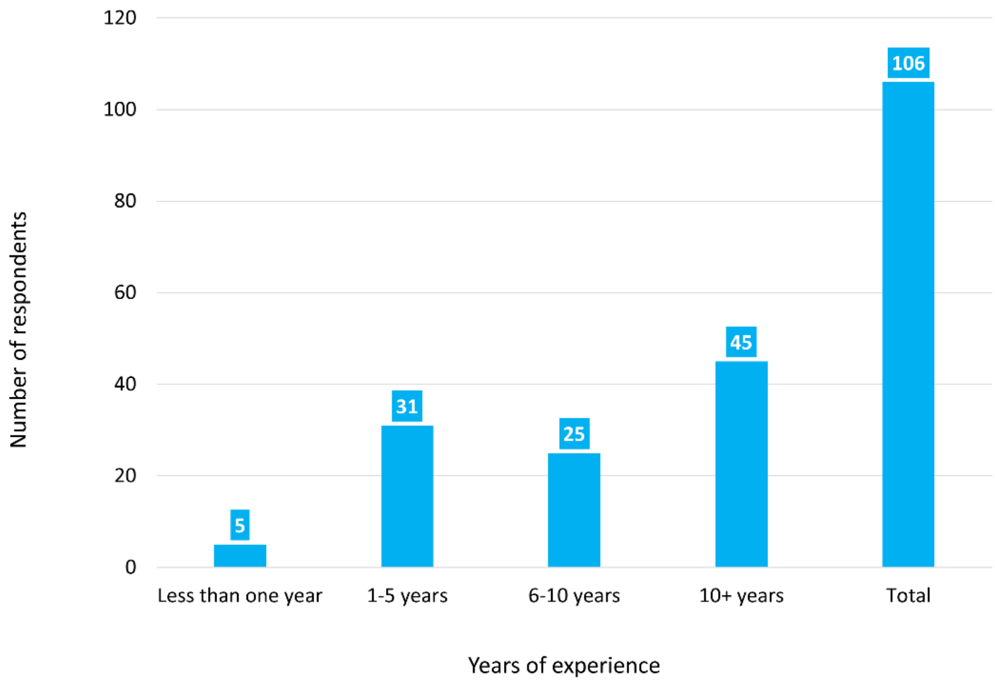


Figure 42: Years of experience of the respondents to the online questionnaire

Internal reliability was used in this research to ensure whether the indicators that make up the scale or index are consistent. Internal reliability performed by using Cronbach's Alpha incorporated into computer software for quantitative data analysis. Two Likert scale questions were analysed in SPSS separately to assess the internal reliability. The first question asked the participants to rate their knowledge in different areas including conceptual structural design, detail structural design, structural analysis, structural optimisation, structural design, automation, generative design/parametric design, and interoperability with other disciplines. The second question asked the participants to rate their computer tools skills in different stages including conceptual structural design, detail structural design, structural design analysis, and structural design optimisation. Table 11 and 12, indicates a Cronbach's Alpha value of 0.866 and 0.797 for the first and second Likert scale question, which are greater than 0.7 and indicates a high level of internal reliability.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.866	.868	7

Table 11: Reliability test for the first Likert scale questions

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.797	.803	4

Table 12: Reliability test for the second Likert scale questions

Table 13, demonstrates the detailed analysis of two Likert scales, which provided interesting results. According to the results related to the first question, if any item of conceptual structural design, detail structural design, structural analysis, structural automation and generative design/ parametric design was deleted the value of Cronbach's Alpha would be reduced which shows a good level of understanding of the respondents in these areas. On the other hand, if the item of interoperability with other disciplines was deleted, the Cronbach's Alpha would be increased to .872, which shows a lack of knowledge in this area. The results of the response to the second question demonstrated that respondents have a good computer tools skills in structural design, detail structural design, structural design analysis. However, these results demonstrated that the Cronbach's Alpha would be increased if the results related to the conceptual structural design deleted, which shows a lack of computer tools skills at the early stage of the structural design.

First question		Second question	
Item	Cronbach's Alpha if Item Deleted	Item	Cronbach's Alpha if Item Deleted
Conceptual structural design	.841	Conceptual structural Design	.811
Detail structural design	.836	Detail structural design	.697
Structural analysis	.840	Structural design analysis	.714
Structural design Automation	.825	Structural design	.757
Generative design/ parametric design	.841		
Interoperability with other Disciplines	.872		
Cronbach's Alpha	**.866**	**Cronbach's Alpha**	**.797**

Table 13: Detailed analysis of two Likert scales

3.13 Ethical consideration

Ethical concerns are greatest when human participants are involved (M. N. K. Saunders, 2019). Therefore, the researcher is responsible for acknowledging any ethical issues or risks and following the required ethical codes and guidelines to ensure participants' identity is protected at all times

(Creswell & Creswell, 2018). The following explain how this research tackled four main ethical principles in social research:

1. **Harm to participants** has been solved by maintaining the confidentiality of identities
2. **Lack of informed consent** has been solved by providing an informed consent form from the University of Portsmouth (UoP). This form contains the research, aim and objectives, the purpose of the questionnaire and the contact details of the researcher, in case the participants require further clarifications.
3. **Invasion of privacy** has been solved by conducting an anonymous data collection
4. **Deception** has been solved by sending invitation letter including a consent form from UoP

In order to ensure the primary data collection conducted ethically without any issues and dilemmas, potential respondents were given the ability to make an informed decision about the participation. The researcher takes full responsibility and ownership of the research data collection. All the data is kept on a password protected Google drive and the only person who has access to the whole data is the researcher. All the data will be kept for the duration of the research and when it is no longer required, the data will be disposed of securely (e.g. electronic media and paper records / images) destroyed.

3.14 Summary

This chapter provides details of the research methodology and methods applied within this research, which was undertaken from a worldview of positivism, an epistemological consideration, with an abductive approach. This research adopted a Mixed-method Methodology started with qualitative method to extend the knowledge about the existing challenges during structural design and optimisation process. In this process, survey strategy was adopted to reach the research population by using online questionnaires. Thereafter, quantitative methods were adopted to validate the proposed framework and prototype as a potential solution to the existing challenges. In this case, survey (interview) and case study strategies were used to reach the population and demonstrate the workability and generalisability of the prototype. According to the type of the data, data analysis was conducted on the quantitative and qualitative data. SPSS and Excel were used to analyse the quantitative data received from the online questionnaire. In this process, Cronbach's Alpha was used to evaluate the internal reliability of the responses to the online questionnaire. Furthermore, NVIVO was used to analyse the qualitative data received from the online questionnaire.

The participants in the semi-structured interview were introduced with the idea of the automatic integration and structural design and analysis in BIM. In addition, they were introduced with the process of alternative conceptual structural design to facilitate the decision-making and optimisation process. Almost all the interviewees were optimistic that the research has the potential to successfully address the proposed issues. They also, suggested to develop the prototype for time-consuming tasks in structural detail design including RC design and providing reports of the design and calculations. Interestingly, several interviewees noted the idea that the prototype is capable to save time and effort during design process. They believed that this prototype needs to be developed to be used in different areas and provide more details about the design automatically. Furthermore, they suggested to develop the prototype for structures with different types of materials such as concrete, timber, aluminium etc. It was also recommended that future development of the design side could be improvement on consideration of more complex buildings. Although, this prototype has been used to design different types of buildings with more complex shapes rather than simple cubic buildings.

Chapter 4: **Framework and prototype development**

This chapter consists of two sections of framework development and prototype development. The first section presents the process of the design, development and validation of the proposed Structural Design and Optimisation (SDO) framework in BIM. This section explains how the Conceptual Structural Design (CSDO) framework is developed by using the findings from the literature review (chapter 2). Thereafter, it details the development of the extended version of the framework, which is based on the results of the data analysis of the online questionnaire. Finally, a proof of concept prototype is detailed to demonstrate the workability of the SDO prototype in a real project.

4.1 CSDO framework development

Initially, a comprehensive literature review was conducted to highlight the existing challenges during the structural design, analysis and optimisation processes. Findings from the literature review were used in the design and development of the Conceptual Structural Design Optimisation (CSDO) framework. Figure 43 demonstrates the rationale of the CSDO framework.

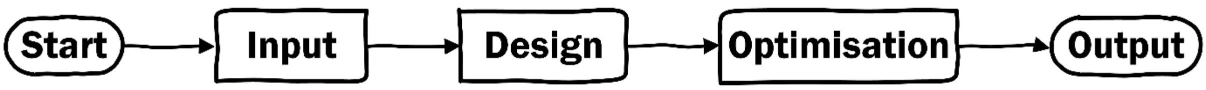


Figure 43: Initial idea of the Conceptual Structural Design Optimisation (CSDO) framework

The process CSDO framework started with the information from the architectural model to generate conceptual structural models. This framework argued that having a system to generate a range of alternative conceptual structural models at the early stages, increases the designers' capabilities to select the most appropriate model among alternative options. Therefore, the focus of the research was first automatic integration between the architectural and the structural design and then automatic structural design and optimisation. In this case, Genetic Algorithms (GA) was considered a potential optimisation method for the framework, which generates a population of solutions rather than optimising a single solution (figure 44).

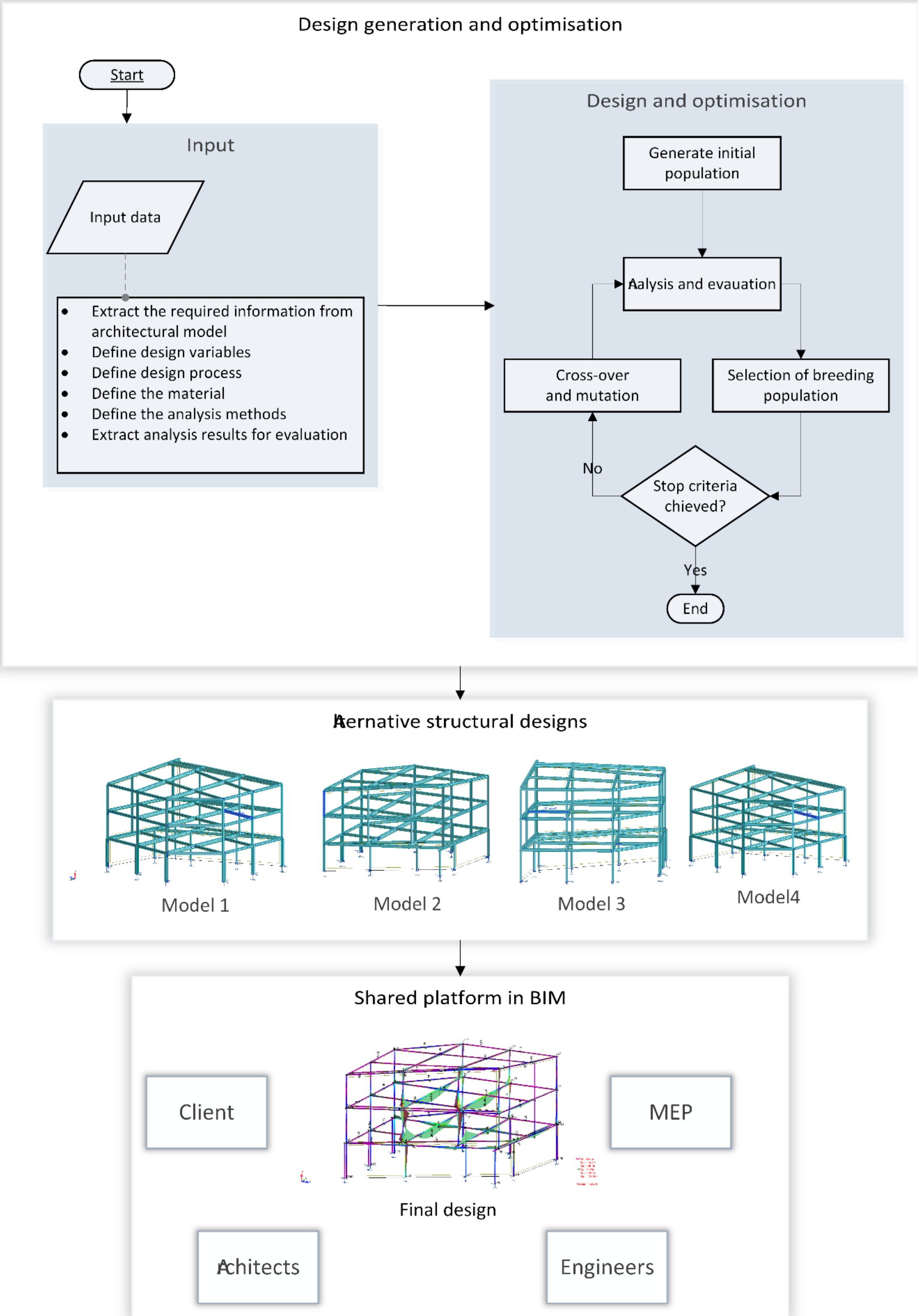


Figure 44: Conceptual Structural Design and Optimisation (CSDO) framework.

The CSDO framework proposed an automatic process of the structural design at the early stages in BIM environment. This framework aimed at assisting the engineers by reducing the time and effort during the iterative structural design at the early stages. This framework involved three stages to make decisions as following:

Design generation and optimisation: This stage begins with the integration between the architectural model and structural model and defining a number of criteria for the structural design process. In this process, the system extracts the required information from the architectural model for the structural design process. In addition, the designer defines parametric design variables to use the architectural information and generate alternative structural models. These design variables including type and number of cross sections, material, loading conditions and supporting systems etc. More design variables generates more alternative structural models with various criteria and provides the designers with a wider scope of alternative structural models to select the optimum solution. All the generated structural models go through the analysis process to evaluate the strength of the structure. Subsequently, the optimisation process continues until the generated solutions meet a certain criteria.

Alternative structural design evaluation: This stage evaluates different alternative structural models and proposes the most optimised structural models in terms of strength and economy. This stage uses the results of the structural design analysis such as bending moment, maximum stress, deflection etc. to compare different alternative solutions and select the best solution. Decision on the type of the analysis result for design evaluation depend on the designers' requirement.

Shared platform in BIM: After final structural evaluation, the most optimised model will be sent for further modification in the BIM environment. All the modifications will take place in central BIM software using the advanced BIM modelling feature.

4.2 SDO framework and prototype development

Extended version of the framework is developed based on the results of the data analysis of the online questionnaire. As discussed in section 3.10.2.1, the current issues during the structural design process related to the time-consuming tasks at the early stage. Furthermore, thematic analysis showed that interoperability between structural engineers and architects is one of the most challenging tasks at the early stages. In order to propose a more specific and practical framework, on top of the automatic structural design and optimisation, this research focused on the integration and collaboration between structural engineers and architects. Therefore, it was decided to expand the framework and improve the efficiency of the integration between structural design and architectural models. In this case, the question was how to integrate these two disciplines in an automatic process and use the architectural information for the automatic structural design process.

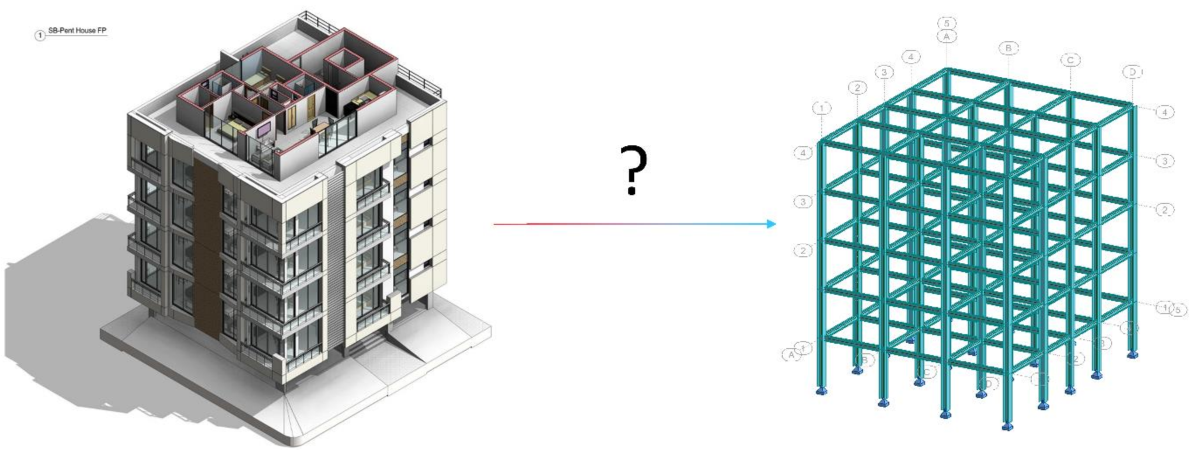


Figure 45: Automatic integration between architectural design and structural design

A comprehensive literature review in chapter 2 highlighted that there are a considerable number of studies on the automatic based structural design and optimisation. However, there is a limited number of research investigations on the integrated structural design, which starts with an architectural model and generates alternative structural models. Moreover, the results of the online questionnaire data analysis showed that there is a need to have an automatic system for integration between architectural and structural models. In addition, respondents to the online questionnaire suggested that BIM technology is the most suitable platform for the framework to improve the collaboration and interoperability between architectural and structural models. Therefore, the extended version of the Structural Design and Optimisation (SDO) framework was developed and aimed at improving the integration and interoperability between the architectural and the structural model in an automatic process in BIM. In this process, parametric information of the models in BIM technology was the main method (design variables) to integrate the architectural model to the structural model. Moreover, this information was used to design and optimise alternative structural models based on the architectural model. Figure 46 demonstrates a schematic process SDO framework, focused on solving the existing challenges and addressing the requirements of the industry – as reflected in the responses submitted to the online questionnaire. Three optimisation methods of shape, topology and size optimisation of the structural design, were used in a BIM-based platform to use the parametric data from architectural model in Revit (Autodesk, 2019a); use the data in the mathematical predefined functions in Dynamo to generate, analyse and optimise different options of structural models in Robot Structural Analysis (RSA) (Autodesk, 2019b). The procedure initiates with the structural shape generation and optimisation by defining mathematical functions and parametric shape variables to create structural geometric entities (see Figure 46). Thereafter, structural topology and size optimisation begins through a structural performance assessment process to generate different integrated options of structural designs during the early stage. In this process, every set of design variables in Dynamo mathematical functions defines a structural model in Robot. Hence, numerical variables and mathematical functions enable the designer to vary the structural shape and the structural topology of the building and optimise the structural elements size in an easier and quicker automatic process.

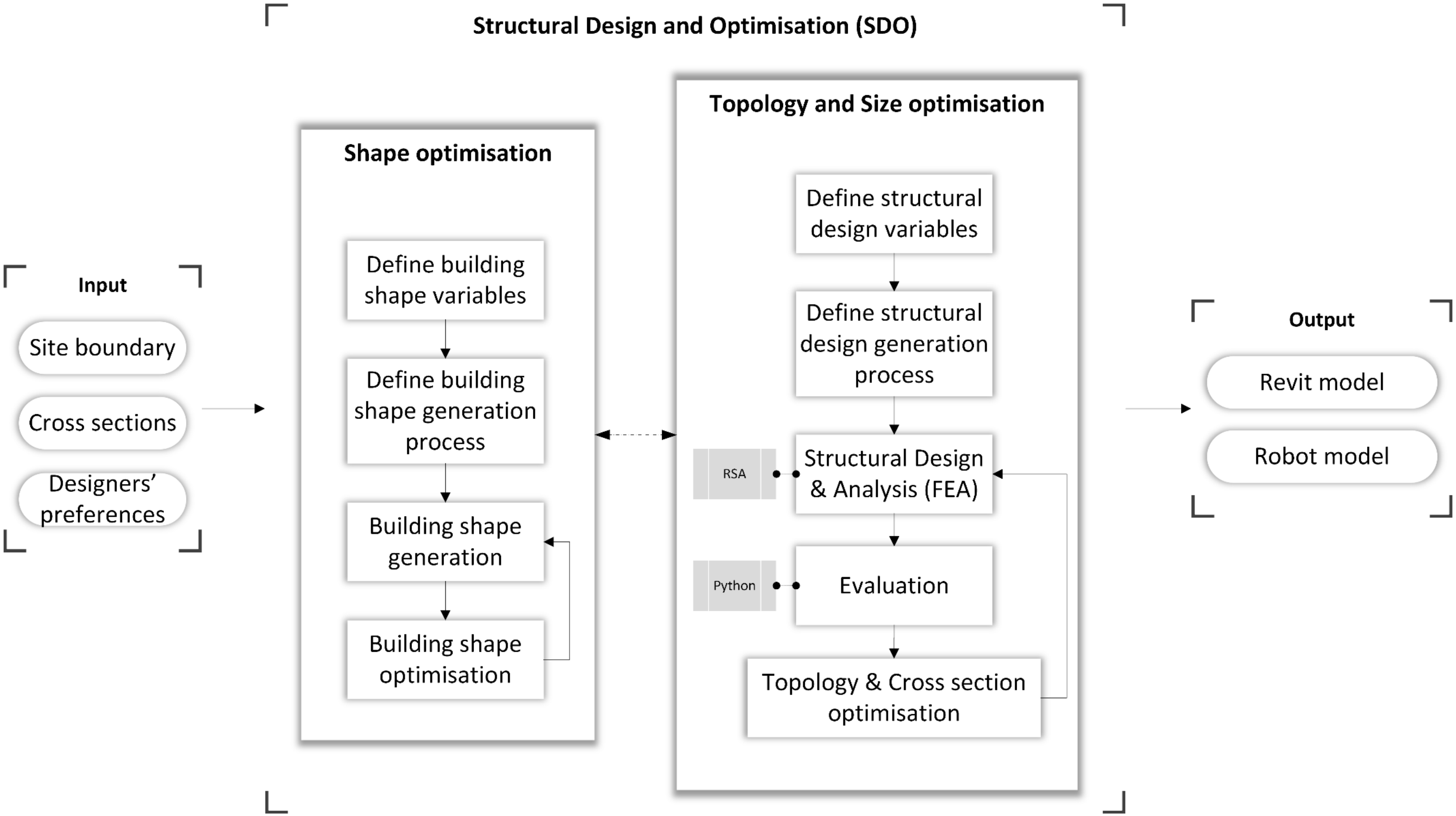


Figure 46: Extended version of the Structural Design and Optimisation (SDO) framework.

The extended SDO framework includes four main sections as discussed in the following sub sections.

Input

This section is about the input data that enables the structural designer to decide on the extracted information from the architectural model and the approach to generate alternative structural models. For example, the site boundary of the architectural model is a critical information from the architectural model to position the building in its accurate location and prevent the building footprint to go beyond the site boundary. Site boundary is utilised in the shape and topology design; hence, structural design is in the exact location of the architectural model. Therefore, defining site boundary dictates the location of structural models. Different methods can be used to define the site boundary such as location of the architectural walls and circumference of different floors. Moreover, input section of the prototype enable the designers to use a list of various cross-sections to design the structural models with and optimise the models by varying the cross sections type and sizes. This section enables the designer to type the name of the cross sections in the relevant node to load the cross section in RSA and generate the structural model by using the cross section (see Figure 47). According to figure 47, node 1 and node2 enable the designer to provide lists of the preferred cross sections to use for the columns and beams in the design respectively. Node 3 and node 4 convert the text to index (code) and provide lists of indexes of the cross sections. Node 5 combines the lists and provides a single list of lists for the indexes. Finally, node 6 loads the required cross sections in RSA according to the input data of the list of lists of cross section names. In this process, changing the text at the first code will affect the entire process and loads a different cross section in RSA.

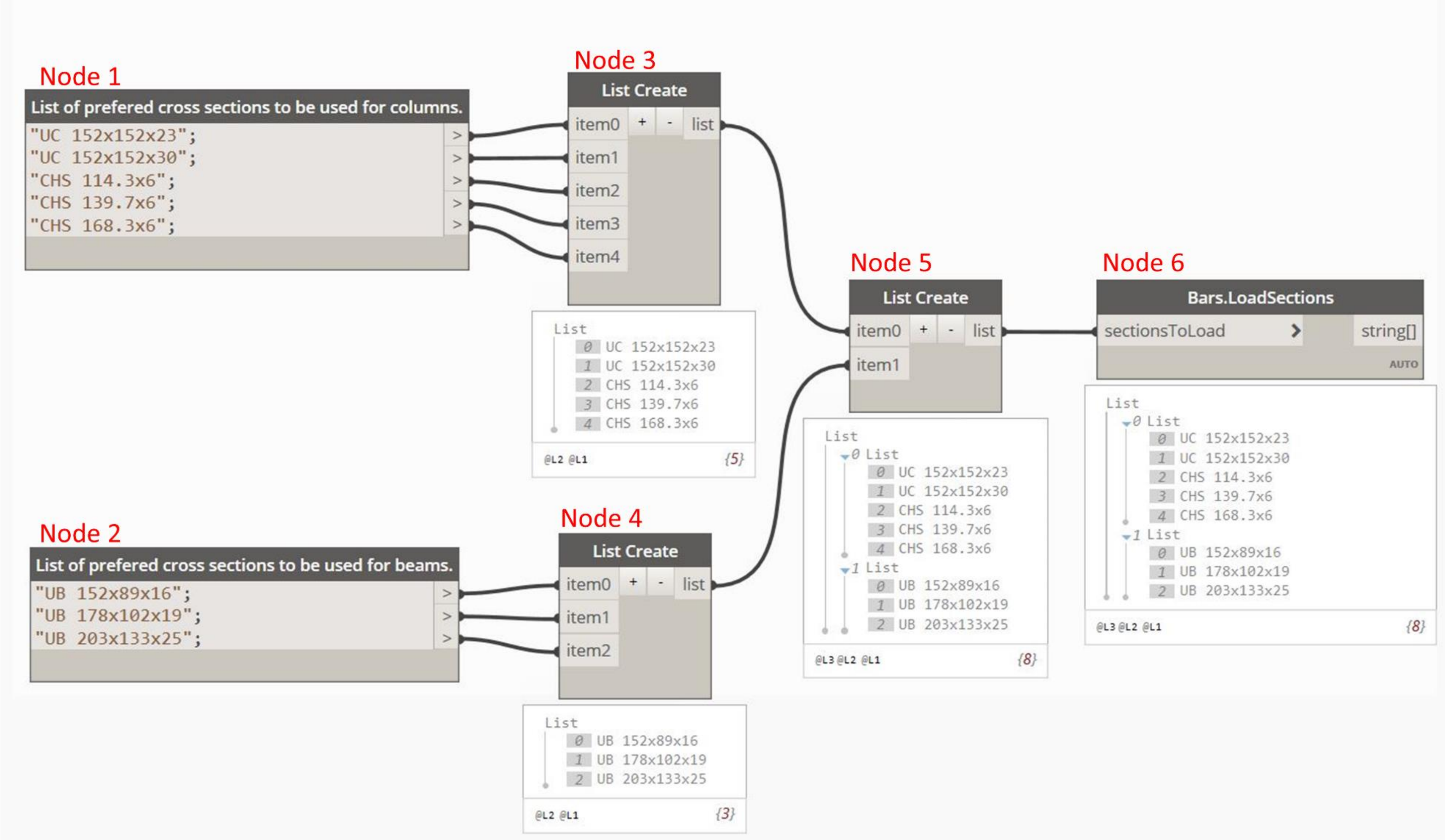


Figure 47: Load different preferred cross sections to use in the columns and beams design separately.

Designers' preferences, as included among the inputs, play a key role in defining mathematical functions and the whole process of the structural design and optimisation. These preferences influence the process of building shape generation, topology optimisation, cross-sections size and the code of structural analysis (Euro-Codes (EC), British Standards (BS) etc.), for structural evaluation purposes. According to the type, shape and complexity of the building, designers can define different mathematical functions to use the input data and design different alternative models by using various cross sections.

Shape optimisation

At this stage, designers define mathematical functions and codes to design the shape of the building by using building shape variables based on their preferences and input data, like site boundary, to generate and optimise the shape of the building parametrically (Figure 59). The visual programming tool (Dynamo) is used to define the mathematical codes and functions and design the building shape generation process. This process uses information including site boundary and building shape design variables to generate different alternative building shapes and optimise the shape of the building by varying the variables in an automatic process. This method enables designers to generate different structural shapes within the required site boundary and optimise the shape of the building by varying building shape variables, which are adjustable, based on designer's preferences. Normally, the architects design the shape of the simple and relatively small buildings and the structural engineers only design the topology of the building and the arrangements of the structural elements. However, this method enables the designers to make efficient decisions where shape of the structure is a governing factor for strength and cost such as design of tall and complex structures.

Topology and size optimisation

According to Figure 46, structural topology and size optimisation process run after the shape optimisation process. That is, any change in the shape of the structural model due to the architectural site boundary will automatically affect the topology arrangements. This link between different stages of the prototype improves the collaboration and integration between architects and engineers through an automated process, by using visual programming language tools (Dynamo). Similar to the shape optimisation stage, topology and size optimisation of structural design are based on structural design variables. Therefore, changing the structural design variables generates different alternative structural models with different topology arrangements and various elements cross-sections sizes, automatically. On the other hand, these structural design alternatives are synchronised to the architectural model. Therefore, any change and adjustment to the architectural model (boundary conditions) or engineers' preferences (topology arrangement and/or elements' cross-sections size) automatically updates the structural design and generates new models. Figure 48 demonstrates the input data nodes for the topology design and arrangement. In this figure node 10 is the main part, which includes 4 parts including: story height (floor height), number of columns, column section index (type of cross section for columns) and beam section index (type of cross section for beams). Node 11 demonstrates the results of the floor height, which are between 2.7 m until 3.2 m with the increase of 0.1m. Node 12 demonstrates the number of columns in the walls, which are between 2 to 6 with the increase number of 2 columns. According to this figure, the prototype will generate alternative structural models with 2, 4 and 6 number of columns in the walls. The values all are parametric data and influenced by the design variables in node 7 and node 10. Node 7 defines the magnitude of increase in number of columns and height of walls. Node 10 defines the lowest and the highest limits. Finally, node 13 and 14 demonstrates the indexes of the cross sections for the columns and beams respectively which explained in figure 47. Any change in the input data for the type, size and number of the cross sections in the previous part affect this section and consequently the results of the alternative structural models.

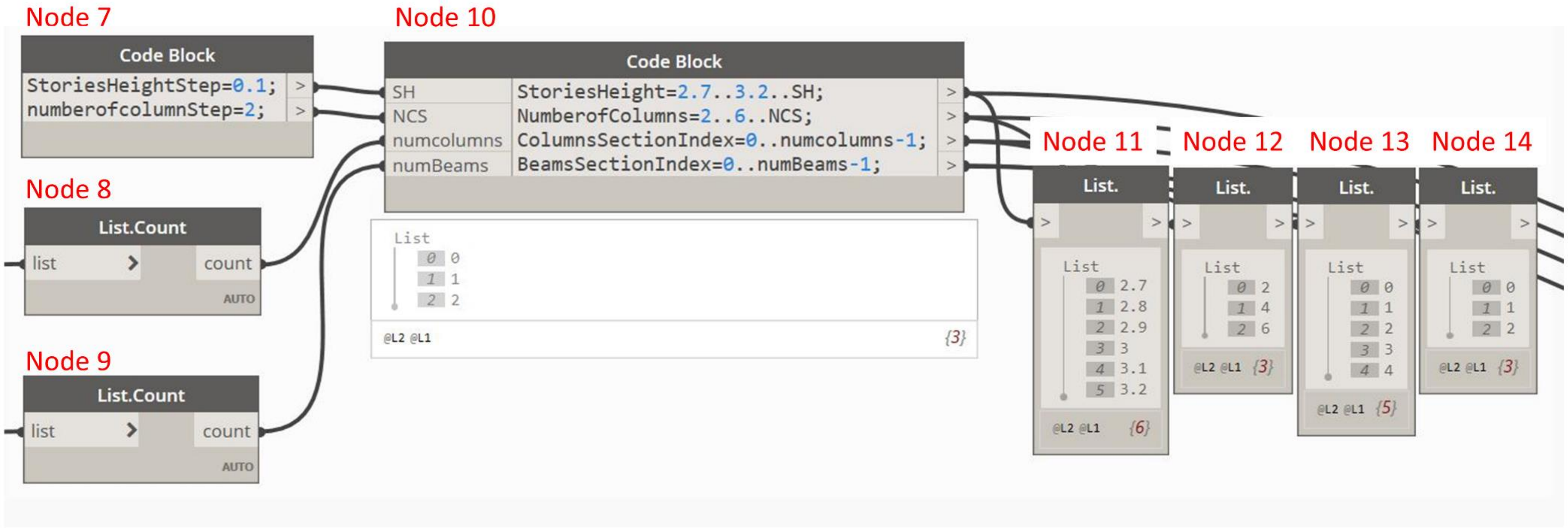


Figure 48: Provide design variables for topology design and to generate different alternative structural models

At the next stage, before defining the structural design generation process, the framework combines all the parametric input data randomly and provides the database for the alternative structural design (see figure 49). According to figure 49, node 15 is responsible to combine the received data randomly and generate lists of combined data for the next stage. Figure 49 demonstrates node 15, which receives 4 number of input data including height of floors, number of columns, columns cross section and beams cross section. Node 16 is a separate node, which creates lists for the combined data. Hence, each list presents the data to design a unique structural model. Figure 49 demonstrates 2 lists of input data for the structural models. However, the results of the combination is greater but invisible in the view. The following tables explains how this information will be converted to a structural model:

Model 1:

Height of the floor	2.7 m
Number of columns	2
Columns cross section	Index 0, which is UC 152x152x23.
Beam cross section	Index 0, which is UB 152x89x16.

Model 2:

Height of the floor	2.7 m
Number of columns	2
Columns cross section	Index 0, which is UC 152x152x23.
Beam cross section	Index 0, which is UB 178x1022x19.

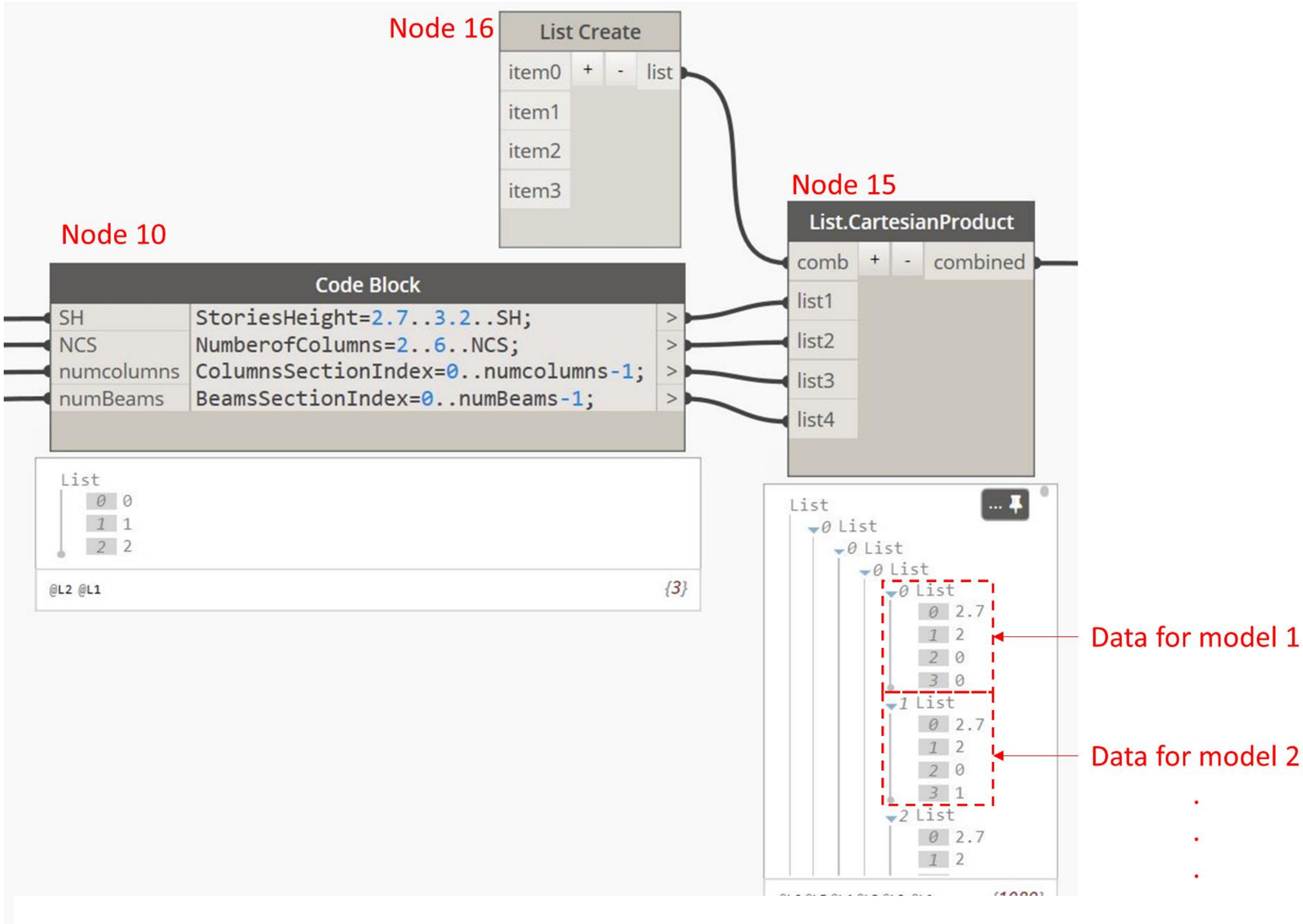


Figure 49: Random combination of the input data to generate lists of input data to generate alternative structural models.

The last part of the structural design and optimisation section of the framework is to use the combined data and additional design variables (x) in a mathematical functions and codes (y) to generate alternative structural models. y , is a function that defines (generates) the result as the structural models for the specific x value. Information of the architectural model are the fundamental part of the prototype to generate alternative structural models based on the architectural model and demonstrate the automatic integration between architectural and structural model. Hence, to show the workability of the prototype in a real setting, an architectural model is provided and this prototype is used to generate different alternative steel frame structural models. The architectural model is a 10x15m residential house without internal load bearing wall, which confirms the need to a steel frame to provide adequate strength to the building. However, the only purpose of this case study is to demonstrate the workability of the prototype in generating alternative structural models for the architectural model. Traditional conceptual structural design for this project requires a time-consuming try and error structural design process. This iterative process prevents the structural engineers from trying various structural models, evaluate them, and select the optimum solution for the detail stage and construction.

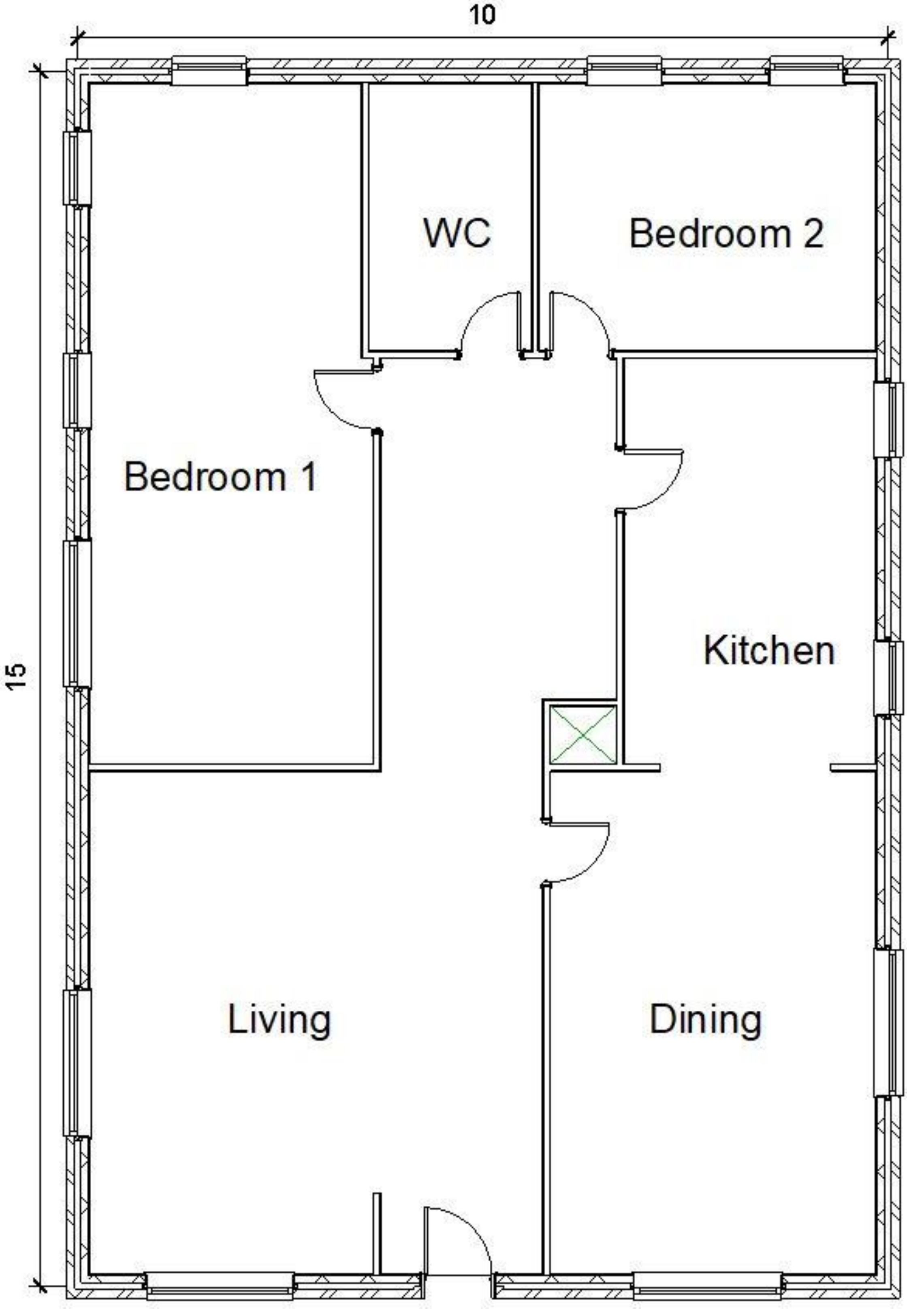


Figure 50: Ground floor plan of the architectural model used to generate alternative structural models by using SDO prototype.

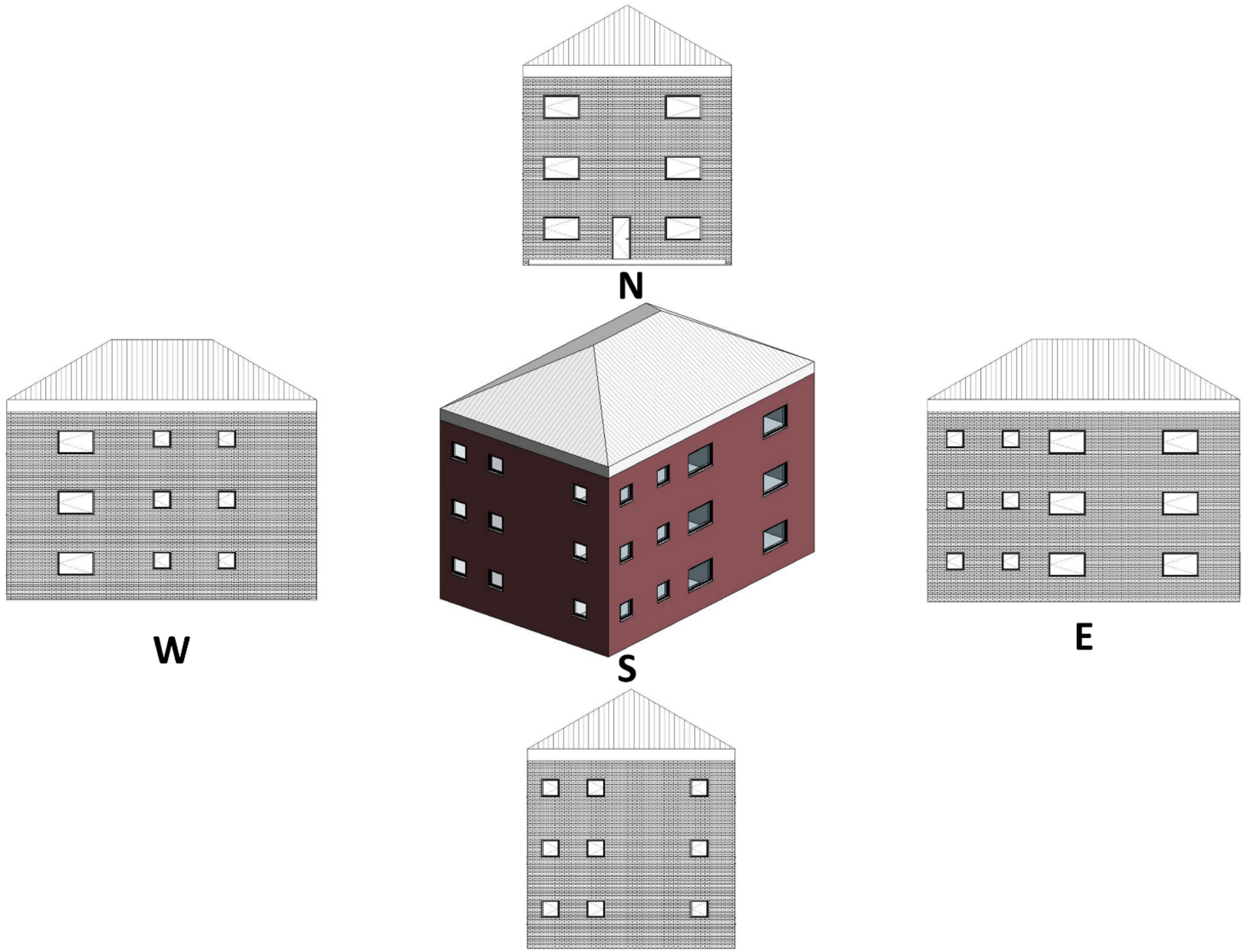


Figure 51: 3D view and elevation views of the building helps the designer to make decisions in defining the mathematical functions and coding to generate structural models for the architectural model.

Figure 52 demonstrates the costume node of SDO Prototype, which is the final stage of the structural design and optimisation process and consists of several nodes and codes, which generate different alternative structural steel frames based on the input data. This function uses eight inputs, of which four of them are design variables (x) that help to generate various designs. As figure 52 demonstrates, these design variables are the lists of combined data from node 15 in figure 49. Therefore, for every list of data, this function generates a unique structural model and this process carries for all the lists of data. Hence, the placeholders for the design variables (indicated with 1,2,3,4 in figure 52) in the SDO prototype are without import link because they are included in the lists of combined data (indicated with star in figure 52). This function uses dead load, live load and type of support as constant variables to explore the best options of the conceptual structural design for the proposed situation and architectural model.

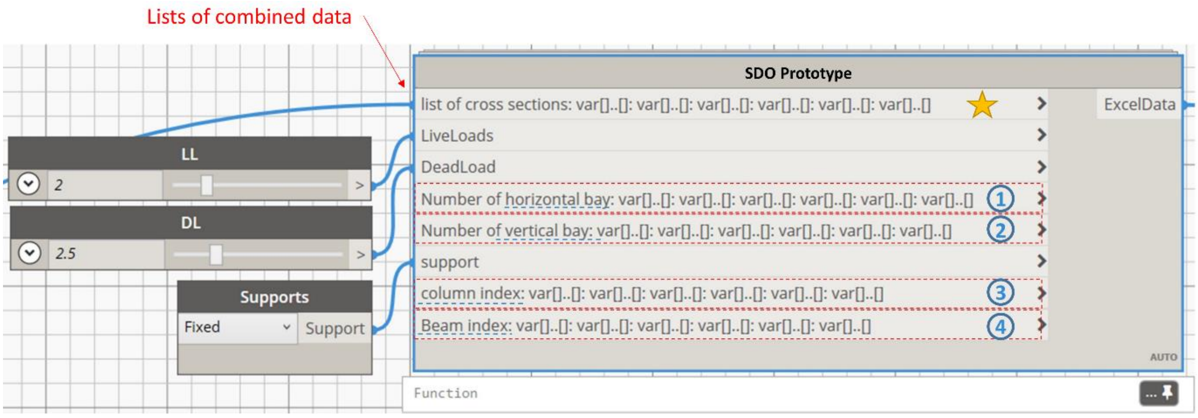


Figure 52: SDO Prototype function to use the input data as design variables and constant variables to generate alternative structural models for the proposed architectural model and loading condition.

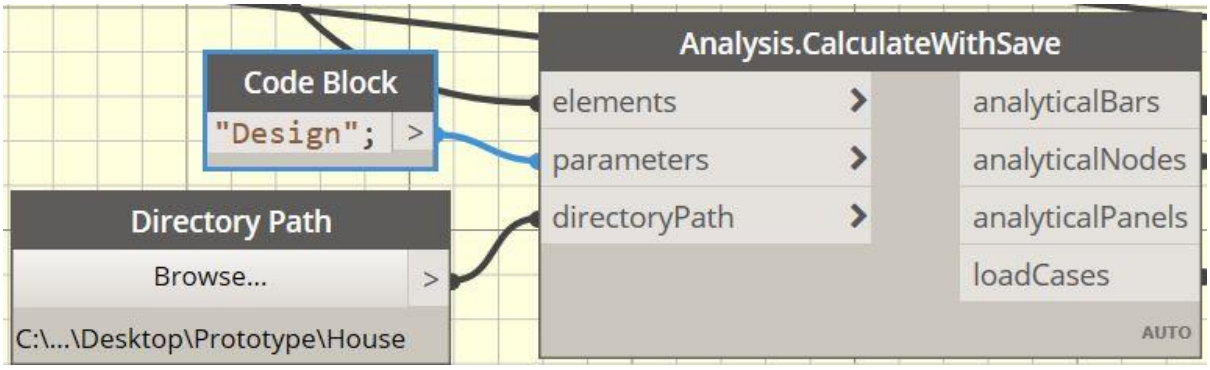


Figure 53: Directory path to save the alternative structural models

Beside the alteration of the input data for the structural design, the SDO prototype uses certain nodes and codes to access the RSA, run the structural analysis for all the alternative structural models, and provide the designer with lists of results of structural analysis. These results include reactions, shear forces, bending moments, stresses and deflections in three axis of x, y and z. Hence, the multidisciplinary node of Analysis.CalculateWithSave is used in the SDO prototype for this purpose, which uses three import, including:

1. Elements: this port takes all the structural elements including information such as the type, size and location of the elements, loading and supporting condition.
2. Parameters: this port help to name different alternative structural models and distinguish them from each other.
3. Directory path: this port defines the location in which all the structural models are saved.

The output of the Analysis.CalculateWithSave node are analytical bars and nodes. Since from the beginning of the structural design in the SDO Prototype beams and columns were defined separately, this node provides separate lists of analytical bars, which represent the columns and beams of the structure. Therefore, all the information of the structural analysis for the columns and beams can be obtained separately. This information enables the designer (engineer) to detailed information of the different alternative structural model and select the best options for detail stage and construction.

Furthermore, SDO Prototype saves all the alternative structural models automatically in the directory path, which has been defined by the designer (figure 53, 54). This enables the designer to open each alternative solution for further modification and optimisation and select the optimum solution.

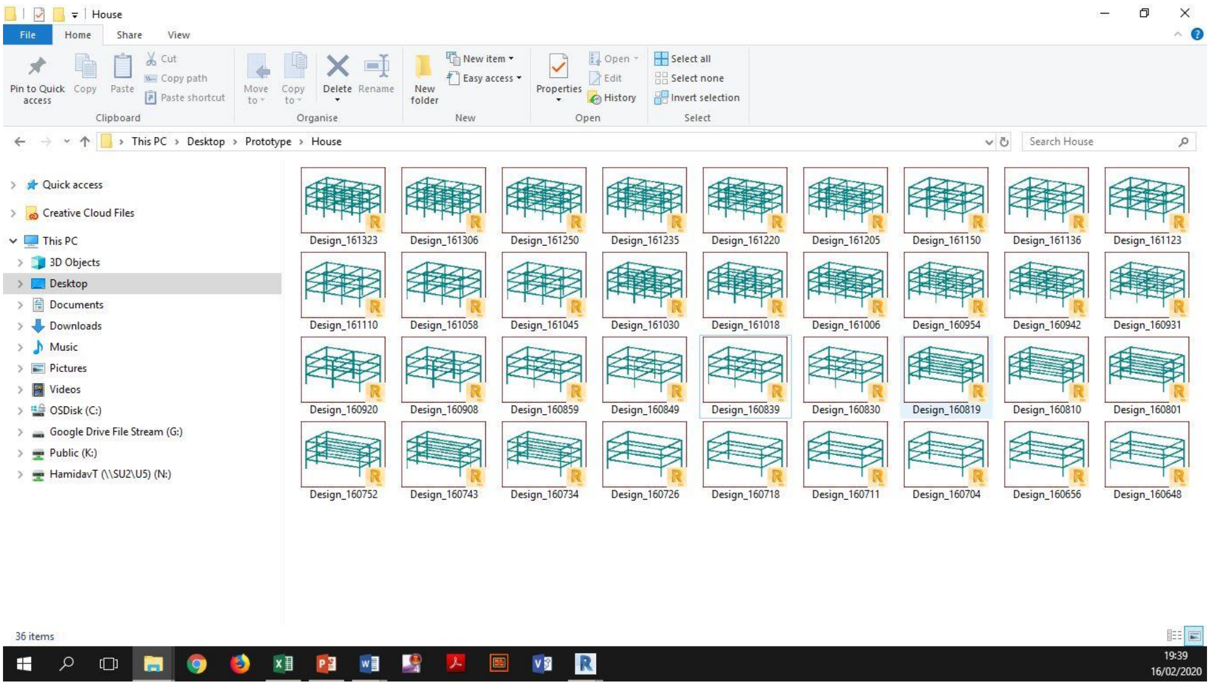


Figure 54: Different alternative structural models saved in the predefined directory path file.

Finally, to help the designers (engineers) with decision-making, SDO Prototype provides a graphical information, which compares and evaluates different alternative structural models. All the information about each design alternative including the number of bays in each direction, number of columns and beams, type of columns and beams cross sections and calculation results will be sent to an already defined Excel file to compare different structural models (figure 55, 56, 57). In the proposed case study self-weight of the structure and maximum stress (S_{max}) of all the alternative structural models were used to compare different alternative structural models. In this case, SDO prototype generates different alternative steel frame structure in which less self-weight represents the less material and more economic structure. On the other hand, less magnitude of the maximum stress (S_{max}) represents the more strength of the building. According to equation 2, the mass of the structure is calculated as the sum of the reactions due to the self-weight load of the structure divided by 9.81 m/s^2 to convert the units from N to Kg (Equation 2 and figure 75).

$$Mass\ of\ the\ structure = \Sigma \frac{Fz}{9.81}$$

Equation 2: Formula to calculate the mass of the steel frame structure from the reactions of the self-weight loading.

One of the features of the RSA is that it applied the self-weight of the structure automatically. Therefore, by changing any element of the structural model it updates the self-weight of the structure according to the mass of the elements. Figure 55 and 56 demonstrate two samples of alternative structural models used to demonstrate how to calculate the mass of the steel frame structure by using the reactions of the self-weight loading. By using equation 2, the total mass of the steel frame structure in the first sample in figure 55 is 3718.65 kg and the total mass of the steel frame of the second sample in figure 56 is 4130.48. This process applies to all the alternative structural models and the results in excel helps the designers (engineers) to evaluate the structural models against the self-weight and to provide an economic conceptual model at the early stage.

$$Mass\ of\ the\ first\ sample\ structure = \Sigma \frac{Fz}{9.81} = \frac{(4 \times 5.35) + (2 \times 7.54)}{9.81} = \frac{36.48}{9.81} = 3718.65\ kg$$

$$Mass\ of\ the\ first\ sample\ structure = \Sigma \frac{Fz}{9.81} = \frac{(4 \times 4.55) + (4 \times 5.58)}{9.81} = \frac{40.52}{9.81} = 4130.48\ kg$$

Figure 58 demonstrates the certain Dynamo nodes and scripts, which extract the data about the reaction results from RSA and use in Excel. In this process, Dynamo nodes extracted only reactions due to the self-weight load of the structure in z direction and applied the equation formula to obtain the whole mass of the structure (figure 58).

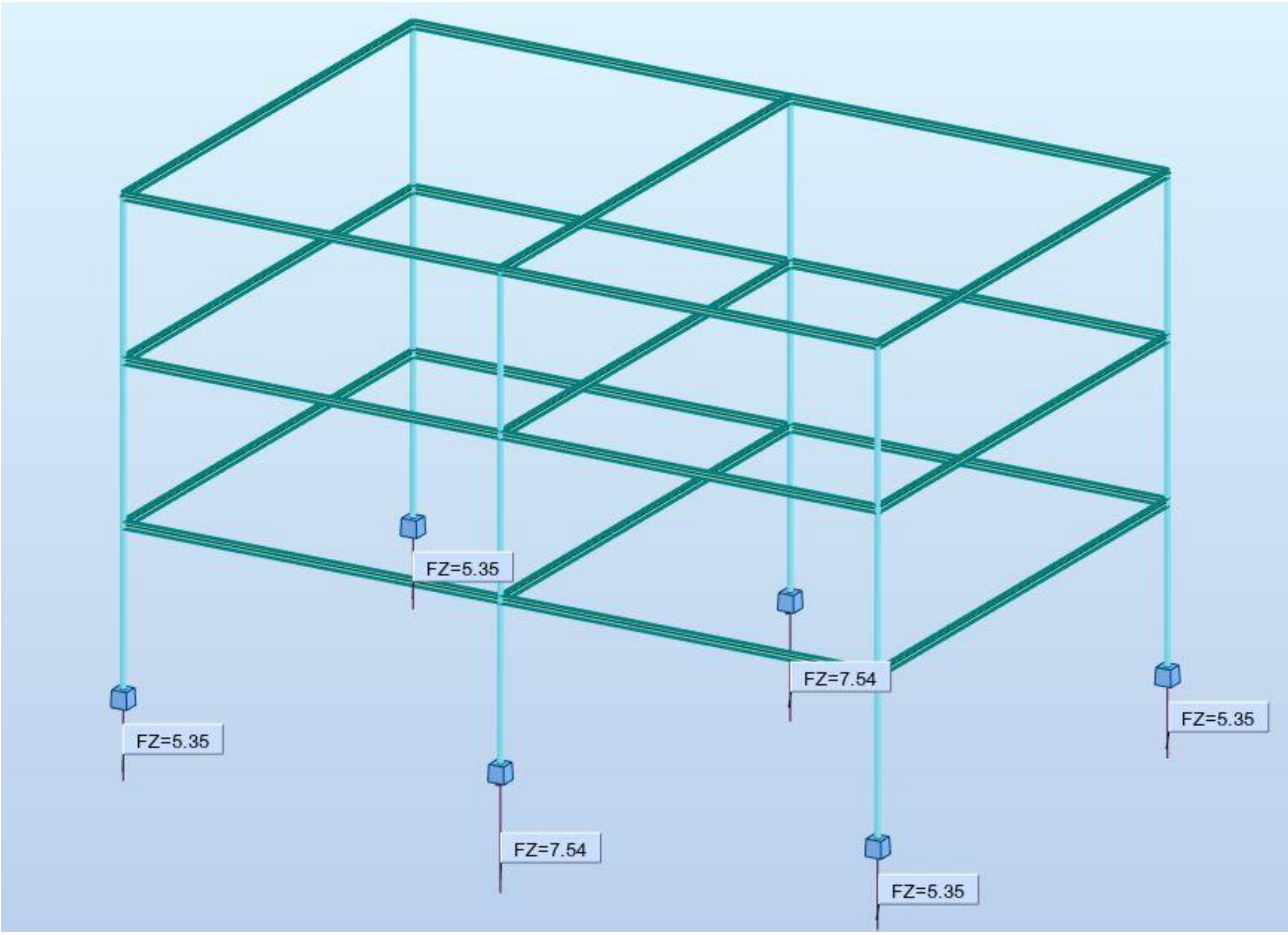


Figure 55: The first sample of calculating the mass of the steel frame by using the reaction of the self-weight load.

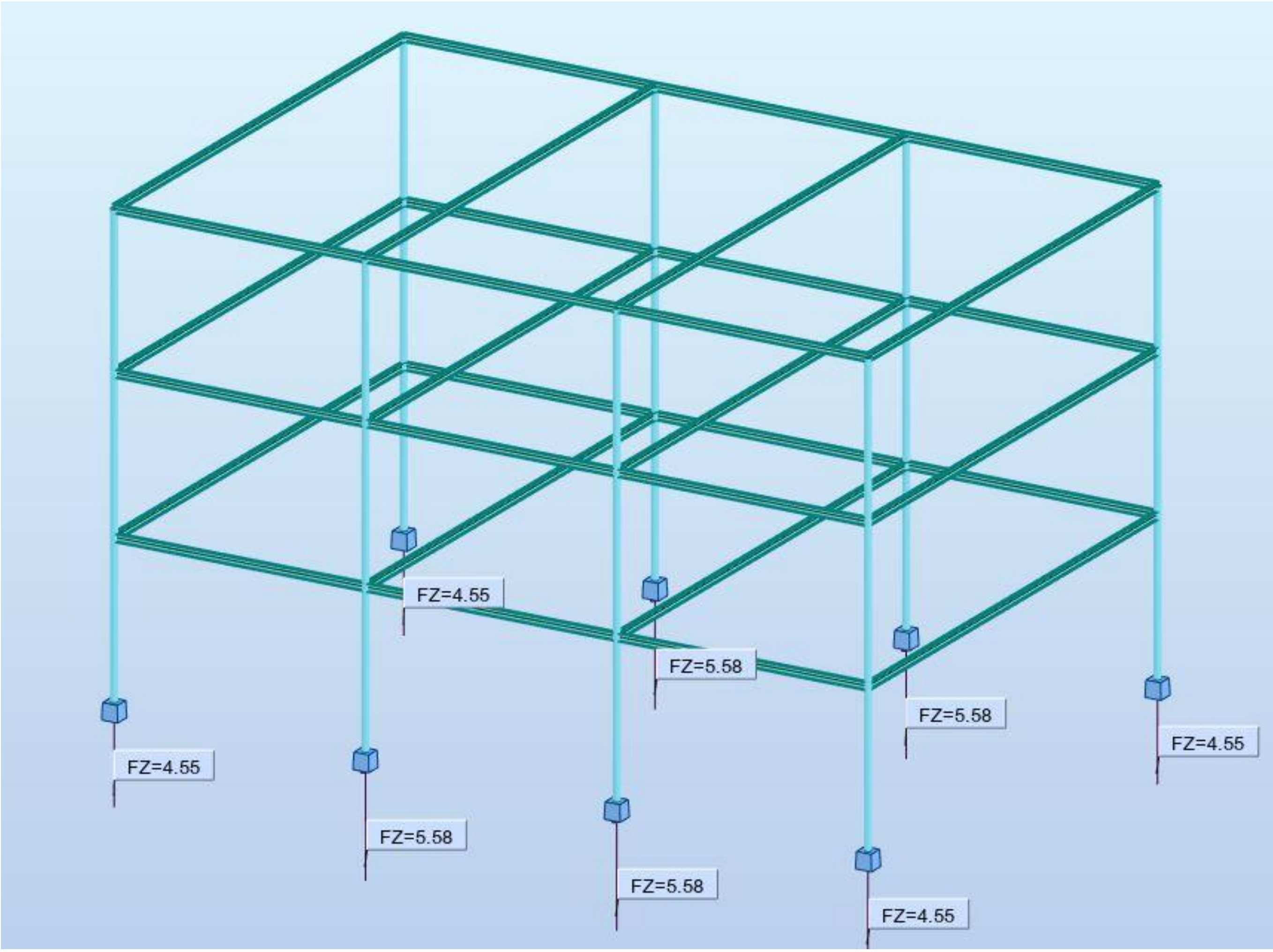


Figure 56 : The second sample of calculating the mass of the steel frame by using the reaction of the self-weight load

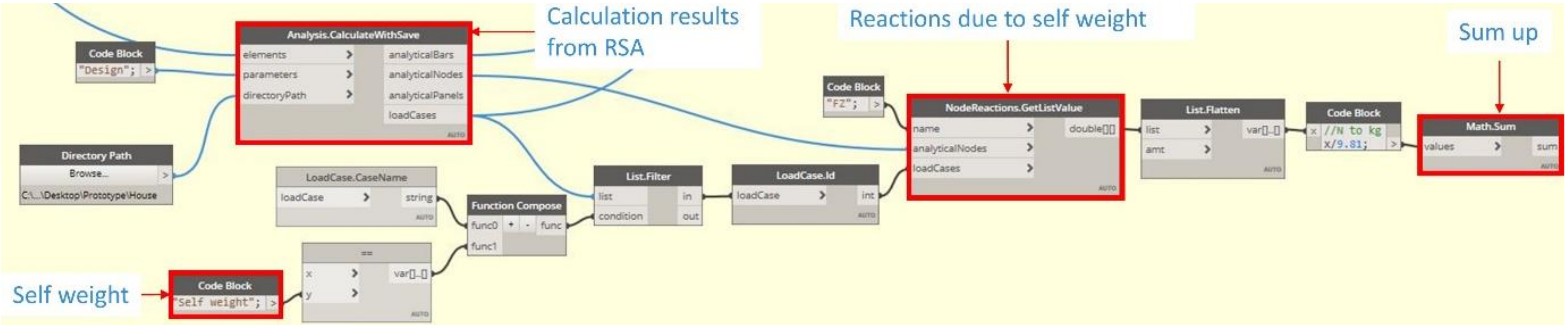


Figure 57: Dynamo nodes and scripts used the results of the structural analysis calculation to calculate the mass of the structure.

The second factor of evaluation, which the SDO prototype used in this case study, is to compare and evaluate different alternative structural models for the maximum stress (S_{max}) in the structural elements from the applied load. In terms of maximum stress (S_{max}), the aim is to use maximum the capability of the structural elements to be strong, stable and economic. Each structural element has specific resistance against the applied load, which is relevant to the strength of the steel (Y: yield strength) and shape of the element (I: second moment of area). Figure 58 demonstrates the yield strength of the two common steel grades (S355 and S275). The steel elements behave elastically until yield strength points (y_1 and y_2). Therefore, the only accepted maximum stress (S_{max}) should be less than the yield strength points (y_1 and y_2). The closer the value of the maximum stress (S_{max}) to zero represents stronger but relatively heavier and less economical structure. On the other hand, the closer the value of the maximum stress (S_{max}) to the yield strength points (y_1 and y_2) represents more conservative design but relatively lighter and more economical design. Hence, the structural designer (engineer) makes the decision on what structural elements is more efficient for their design. Therefore, the following formula (ratio) is defined to evaluate whether the designed structural elements are in the range of acceptable elements or not. In this formula, n and m are parametric variables, which enables the designer to adjust them and define a domain for their requirements.

$$\boldsymbol{n} < Stress\ ration = \frac{\boldsymbol{Maximum\ stress}}{\boldsymbol{Allowable\ stress}} < m$$

Equation 3: A domain to evaluate the maximum stress in the structural elements for the applied load.

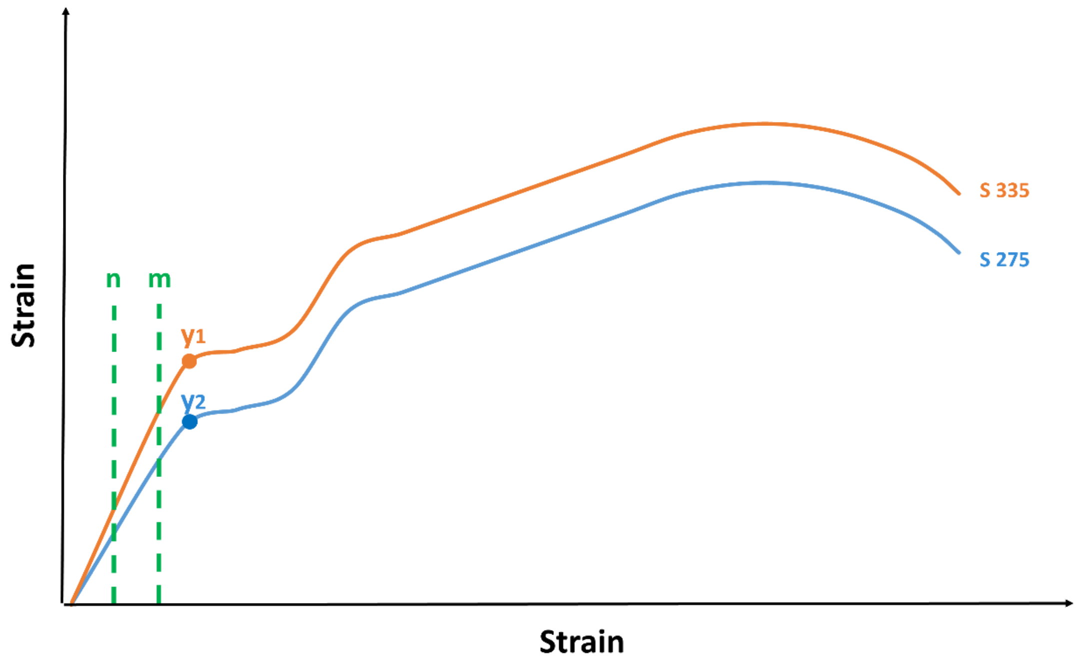


Figure 58: Stress strain curve of two different steel grades

Figure 59 demonstrates the dynamo nodes and codes used in this case study for the SDO prototype to combine all the information of the structural design and structural analysis of each model in a excel file. As figure 59 shows all the information of the excel file is defined in the dynamo environment. Furthermore, this figure shows that the directory path file is defined to save the information in the right file. Figure 60 shows the next stage when all the information sent to the excel file and placed in the right location. According to this figure, row number 7 and 8 in this table are the self-weight and the maximum stress (S_{max}) value for all the alternative structural models designed by SDO Prototype. Therefore, these two rows can be used to demonstrate the results graphically to evaluate different alternative structural models (see figure 61).

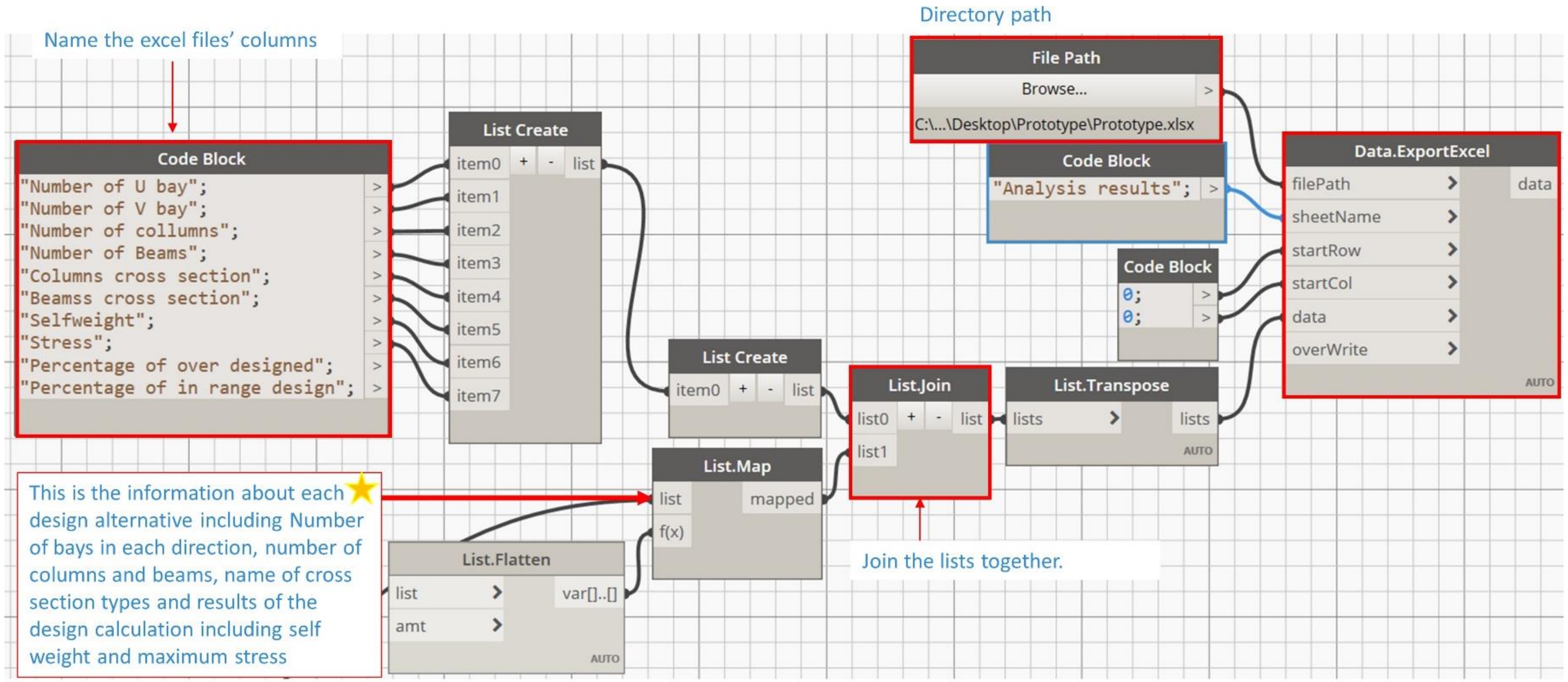


Figure 59: Data export to excel

	A	B	C	D	E	F	G	H	I	J
1	Number of U bay	1	1	1	1	1	1	1	1	1
2	Number of V bay	1	1	1	1	1	1	2	2	2
3	Number of collumns	4	4	4	4	4	4	6	6	6
4	Number of Beams	12	12	12	12	12	12	21	21	21
5	Columns cross section	CHS 114.3x6	CHS 114.3x6	CHS 139.7x6	CHS 139.7x6	UC 152x152x30	UC 152x152x30	CHS 114.3x6	CHS 114.3x6	CHS 139.7x6
6	Beamss cross section	UB 127x76x13	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76x13
7	Selfweight	2509	2955	2645	3090	3015	3460	3378	3957	3581
8	Stress	446	410	401	366	378	343	580	544	509

	A	K	L	M	N	O	P	Q	R
1	Number of U bay	1	1	1	2	2	2	2	2
2	Number of V bay	2	2	2	1	1	1	1	1
3	Number of collumns	6	6	6	6	6	6	6	6
4	Number of Beams	21	21	21	21	21	21	21	21
5	Columns cross section	CHS 139.7x6	UC 152x152x30	UC 152x152x30	CHS 114.3x6	CHS 114.3x6	CHS 139.7x6	CHS 139.7x6	UC 152x15
6	Beamss cross section	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76x13	UB 152x89x16	UB 127x76
7	Selfweight	4160	4137	4716	3184	3718	3387	3921	3942
8	Stress	475	421	376	343	311	313	283	319

Figure 60: Information of all the structural models in Excel. Units for the self-weight is Kg and for the stress is Kn/m2.

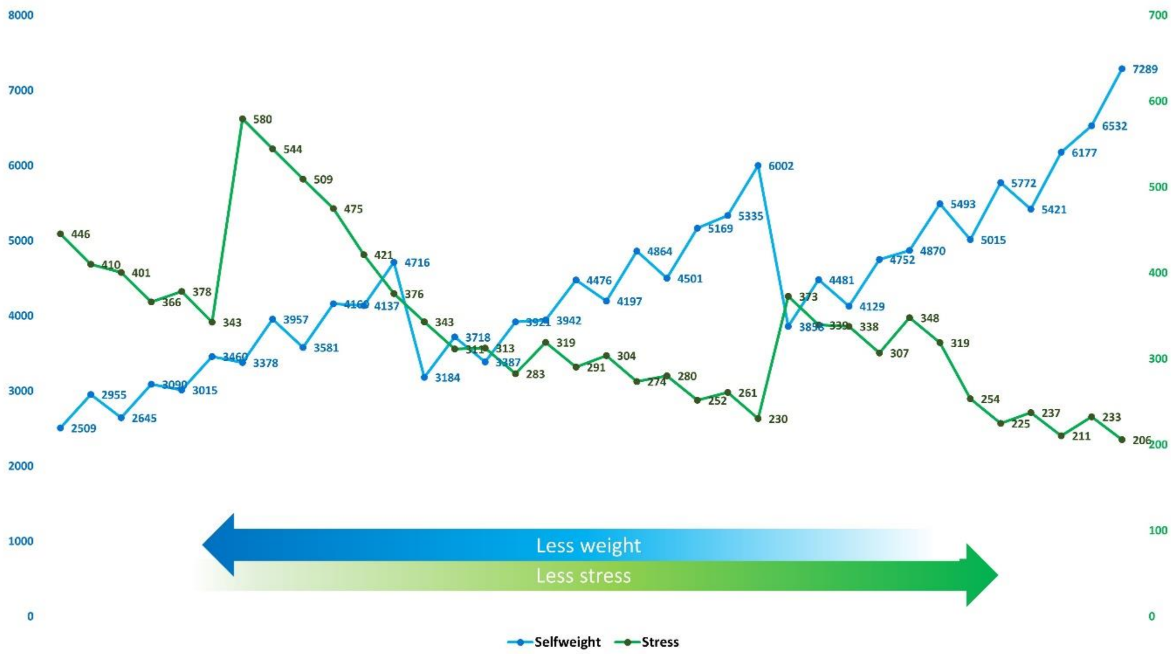


Figure 61: Excel graph to compare alternative structural models. Units for the self-weight is Kg and for the stress is Kn/m2.

Figure 61 shows the results of the structural analysis of different alternative structural models for the same architectural model by using SDO Prototype. This graph shows an increasing trend for the self-weight of the structure from left to right (blue line). On the other hand, the maximum stress (S_{max}) of the structural elements have a decline trend from the left side to the right side. Therefore, the structural models at the middle present economic and at the same time strong structural steel frames. Between these options, structural engineers can select the best option based on their requirements.

4.2.1Genetic algorithm (GA) optimisation

This research used mathematical functions in Dynamo to generate alternative structural models in RSA based on the architectural model and engineers' preferences. This section explains how the

SDO Prototype uses other optimisation methods such as Genetic Algorithms (GA). This research uses the Optimo package in Dynamo to perform Genetic Algorithms (GAs) optimisation on the generated alternative structural models. This package includes all the required nodes and codes to perform the GA optimisation. All the process of structural design and analysis are similar to the previous section and follow the same logic except the data combination and evaluation. As figure 62 shows, this process begins with defining the lower and upper limits of the design variables to generate alternative models within the preferred scope. These limits are parametric values and vary from project to project based on the type of the project and the design process. For example, this case study includes four design variables as following:

1. 1 < number of bays in X direction < 4: this scope shows that the minimum number of bays in the X direction is one and the maximum is four. The prototype generates random numbers between these two numbers to use for the design of alternative structural models.
2. 1 < number of bays in Y direction < 3: this scope shows that the minimum number of bays in the Y direction is one and the maximum is three. The prototype generates random numbers between these two numbers to use for the design of alternative structural models.
3. 0 < Columns section Index < number of column cross sections – 1: this scope shows that the first cross section for the columns has the index of zero and the last cross section for the columns has the index of number of column cross sections – 1. Because the number of index is always one digit less than the number of items in the list.
4. 0 < Beams section Index < number of Beam cross sections – 1: this scope shows that the first cross section for the beams has the index of zero and the last cross section for the beam has the index of number of beam cross sections – 1.

In this process, the ‘NSGA_II.InitialSolutionList’ node generates random design variables based on the population size (in this case study the population size is 10) within the defined scope (lower and upper limits that explained above). This enables the prototype to generate various designs in a certain scope and prevent the system from generating unwanted models, which are beyond the defined scope. In this case study, four design variables have been defined, therefore, NSGA_II.InitialSolutionList node generates four lists with 10 indexes (population size) plus an extra list as a placeholder for the weight score of each solution (figure 62). The first and second lists include 10 random numbers for the bays in the X and Y direction respectively. The third and fourth lists include 10 random numbers for the index of the columns and beams cross sections respectively. After this stage, all the random decimal numbers convert to be natural numbers and the SDO Prototype uses the numbers as input data to design alternative structural models. Thereafter, the prototype access the RSA to run the structural analysis for all the alternative structural models and extract the results of the analysis similar to what explained previously.

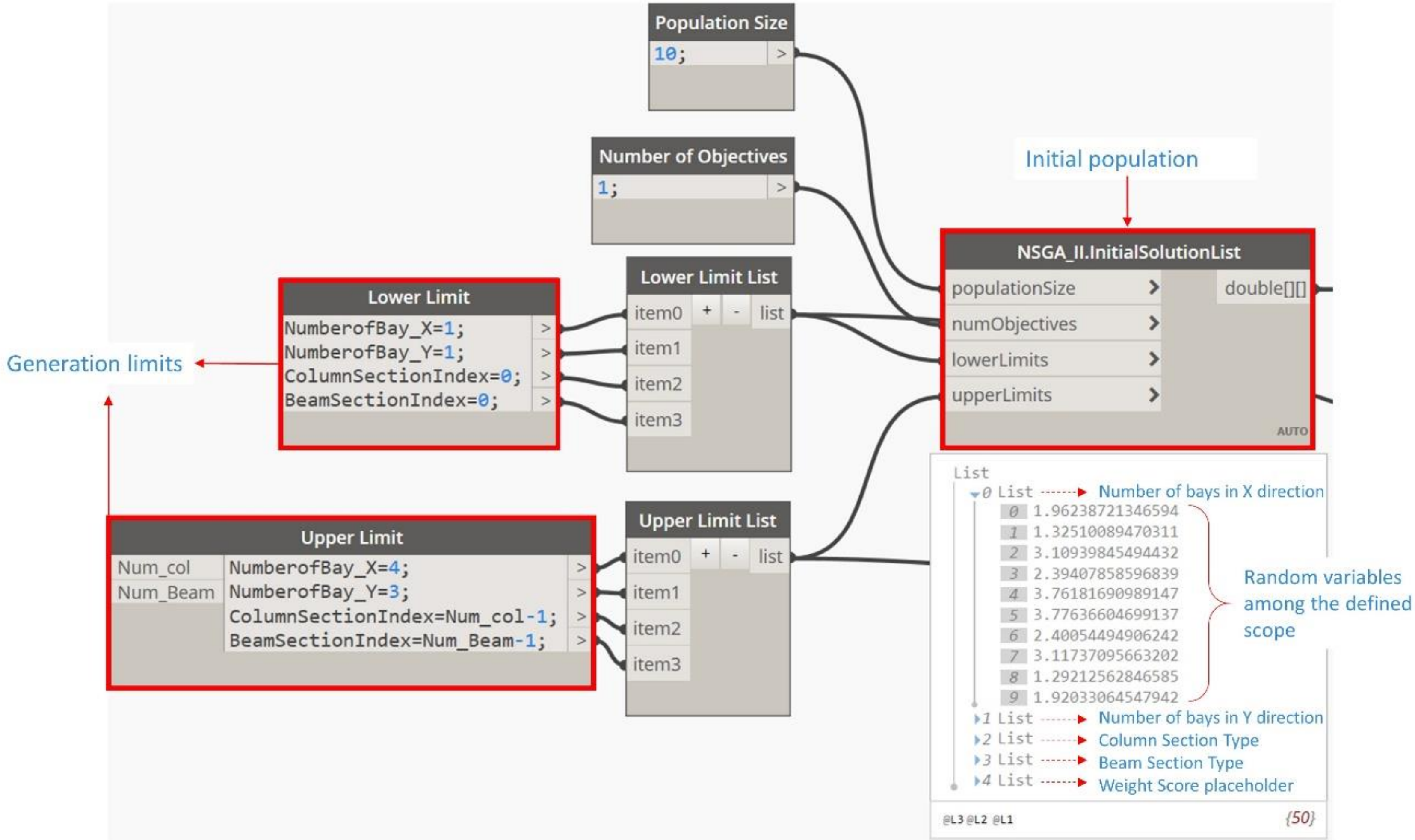


Figure 62: Generating random initial population by using Genetic Algorithm (GA) in Dynamo

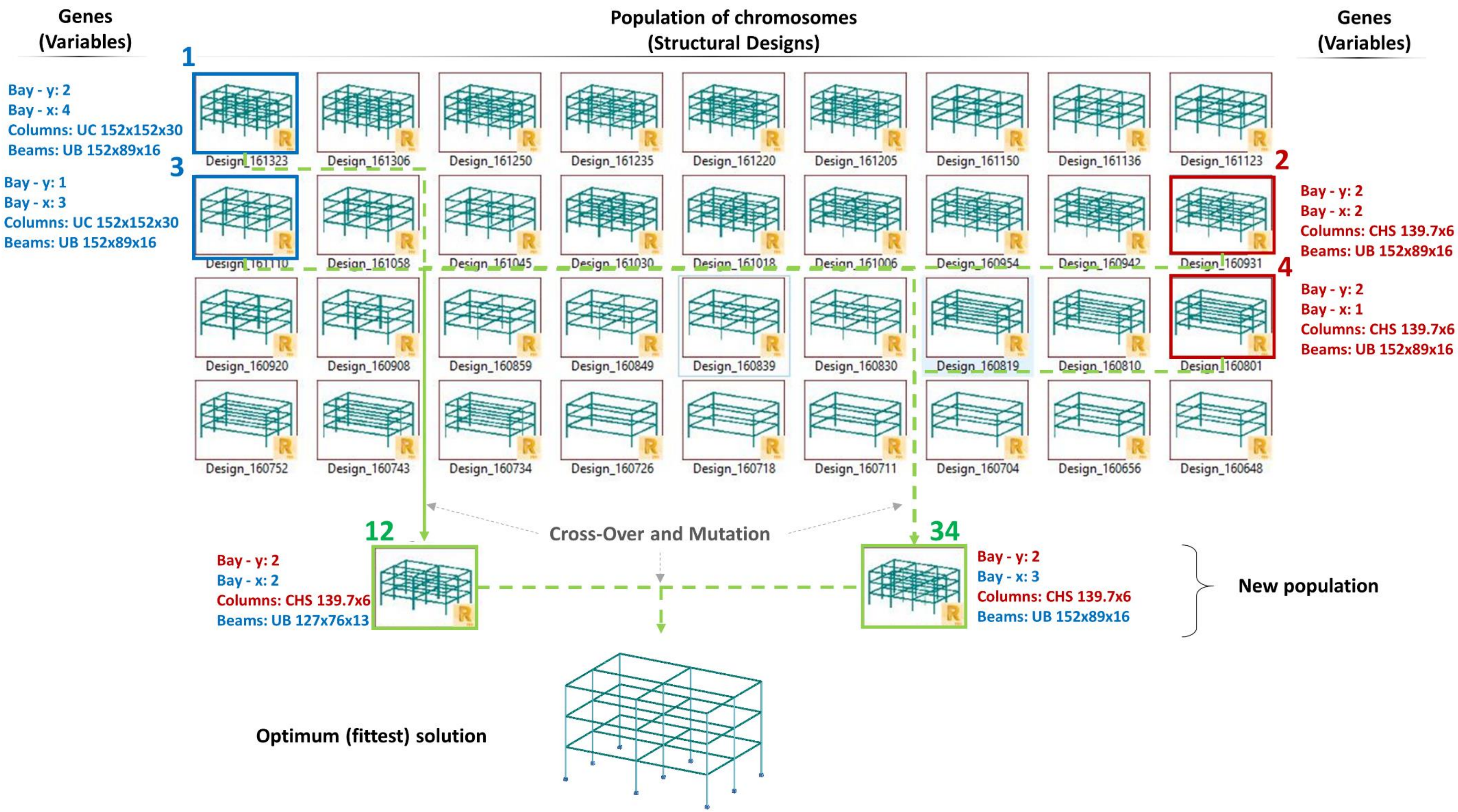


Figure 63: Genetic Algorithm (GA) used to generate random initial population and perform the structural optimisation using cross over and mutation.

Figure 63 demonstrates how the SDO Prototype uses the GA to design and optimise alternative structural models. In this process, GA generates random initial population of the alternative structural models based on the input data of the design variables. In this population, each model represents a chromosome, which includes certain types of genes (design variables) and weight score. In this process, cross over and mutation performs on the generated models (parents) to combine design variables (genes) and generate new solutions (off springs). For example, model number 1 and model number 2 in figure 63 with different design variables (genes) combines and generated new model number 12. Model number 12 includes half of the design variables from model number 1 and the other half from the model number 2. On the other hand, model number 3 and model number 4 combined and generated new model which is model number 34. In this case, one of the design variables is from model number 4 and the rest of the design variables are from the model number 3. SDO Prototype uses codes that performs these variations (cross over and mutation) and generate various types of alternative structural models. In this process variation in the design variables generates various types of structural designs with different weight score (fitness values). In this case study, the objective function of the optimisation was minimum weight score, which is minimum self-weight or mass and minimum number of elements beyond the allowable stress ration.

As figure 58 indicates, the proposed prototype works on a certain region of the elastic area. Any design with a maximum stress (S_{max}) less than n considered as under stress (less than the capability of the steel) which is not economic but still strong to resist against the applied load. On the other hand, any design with maximum stress (S_{max}) more than m considered as over stressed design (more than the capability of the steel) which is not strong enough and may result in a failure in the structure or high deflection. Therefore, these two type of structural models receive two different penalty functions to be excluded from the design loop and only keep the models within the required scope, strong and economic. Thereafter, GA combination engines (crossover and mutation) combines the fitter design solutions (survivors) which results in close to optimum solutions. In this process, designs with over stress members, which result in failure, receive a higher penalty function on other hand; designs with under stressed embers receive lower penalty function. Therefore, the designs, which have all the members with maximum stress (S_{max}) within the required range, between n and m, will receive no penalty function but only the self-weight of the structure as the weight score. On the hand, designs with elements under stressed receive self-weight of the structure plus the applied maximum stress (S_{max}) of the structure to have a higher weigh-score. In addition, those designs, which have elements over designed, receive the self-weight plus maximum stress (S_{max}) to the power of two to make a greater number. Thus, the designs with less weight score will be selected as the optimum solution, which have less mass and all the members within the allowable maximum stress (S_{max}). Figure 64 indicates how the penalty function is used to separate the over design and under design structural models from the optimum designs.

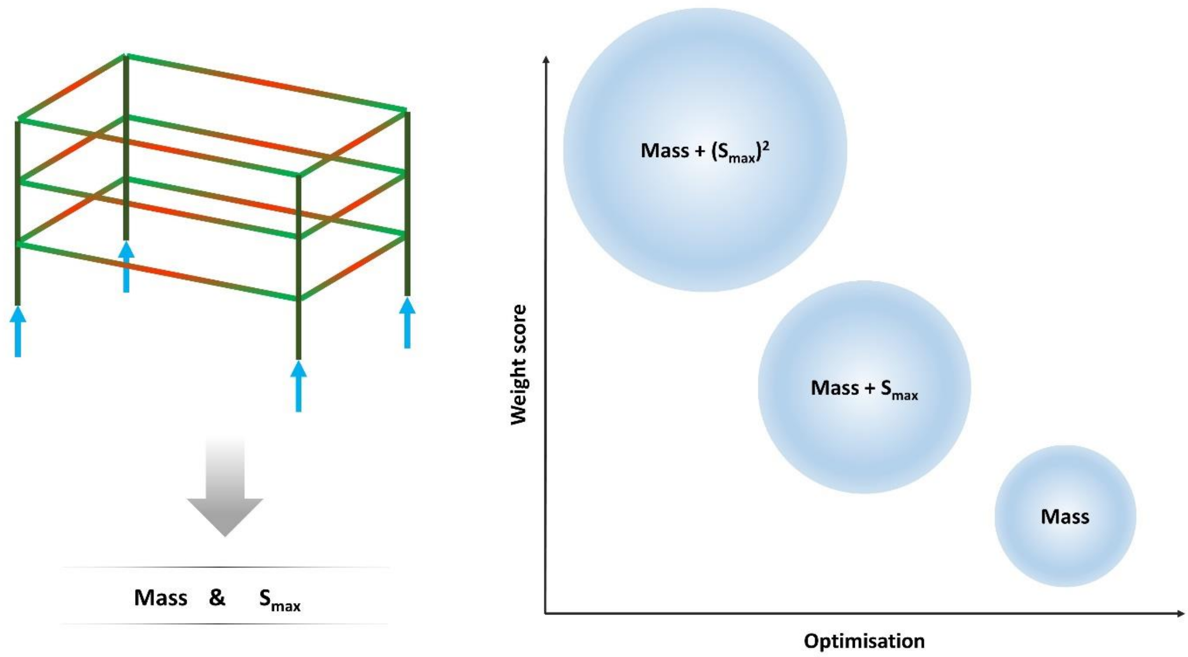
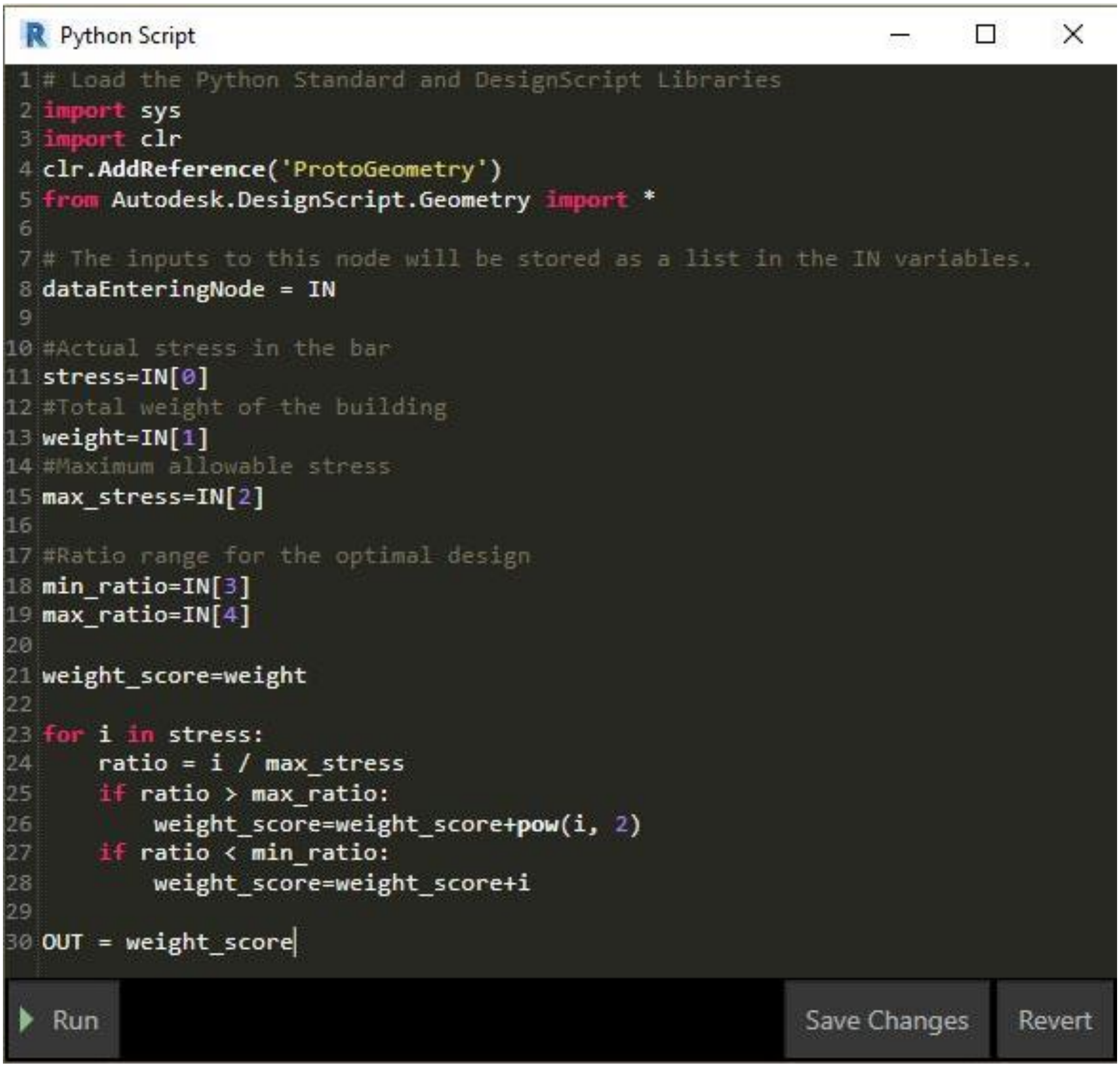


Figure 64: Using Mass and S_{max} to calculate the weight score of different design and perform optimisation process.

Figure 65 shows the Python scripts which use four inputs and to calculate the weight score of the structural model.




```python
# Load the Python Standard and DesignScript Libraries
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN

#Actual stress in the bar
stress=IN[0]
#Total weight of the building
weight=IN[1]
#Maximum allowable stress
max_stress=IN[2]

#Ratio range for the optimal design
min_ratio=IN[3]
max_ratio=IN[4]

weight_score=weight

for i in stress:
    ratio = i / max_stress
    if ratio > max_ratio:
        weight_score=weight_score+pow(i, 2)
    if ratio < min_ratio:
        weight_score=weight_score+i

OUT = weight_score
```

Figure 65: Python scripts to calculate the weight-score of the alternative structural modelsby using penalty functions for the over design and under design structural models.

4.3 Case study

In order to assess the practicality and the potential performance of the proposed solution, The Gherkin Tower is chosen as a case project to demonstrate how architects and engineers can work in an integrated platform and benefit from the structural optimisation process, as proposed. The Gherkin Tower is chosen, because of its elongated, curved shaft with a rounded end design that stands out against the more conservative nature of most of London's buildings. This innovative design is selected as the case project to demonstrate the workability and efficiency of the proof of concept prototype in designing complex and creative designs. Furthermore, the tower's unique shape required ARUP (2020) structural engineers to work closely with Foster and Partners (2004) architects to achieve an ambitious curved form for the tower. Therefore, the proposed prototype demonstrates how one can automate the synergy between architects and structural engineers in a BIM based platform to reduce the design time. The Gherkin tower has two primary structures comprising the diagrid and the core. The diagrid is the main part of the structure, which resists the lateral and gravity loads, and transfers it to the core section of the structure. Cantor Seinuk defines diagrid as a series of triangles that combine gravity and lateral support into one, making the building stiff, efficient and lighter, compared to a traditional high rise buildings (Al-Kodmany, 2018; Spray & Ruffle, 2018).

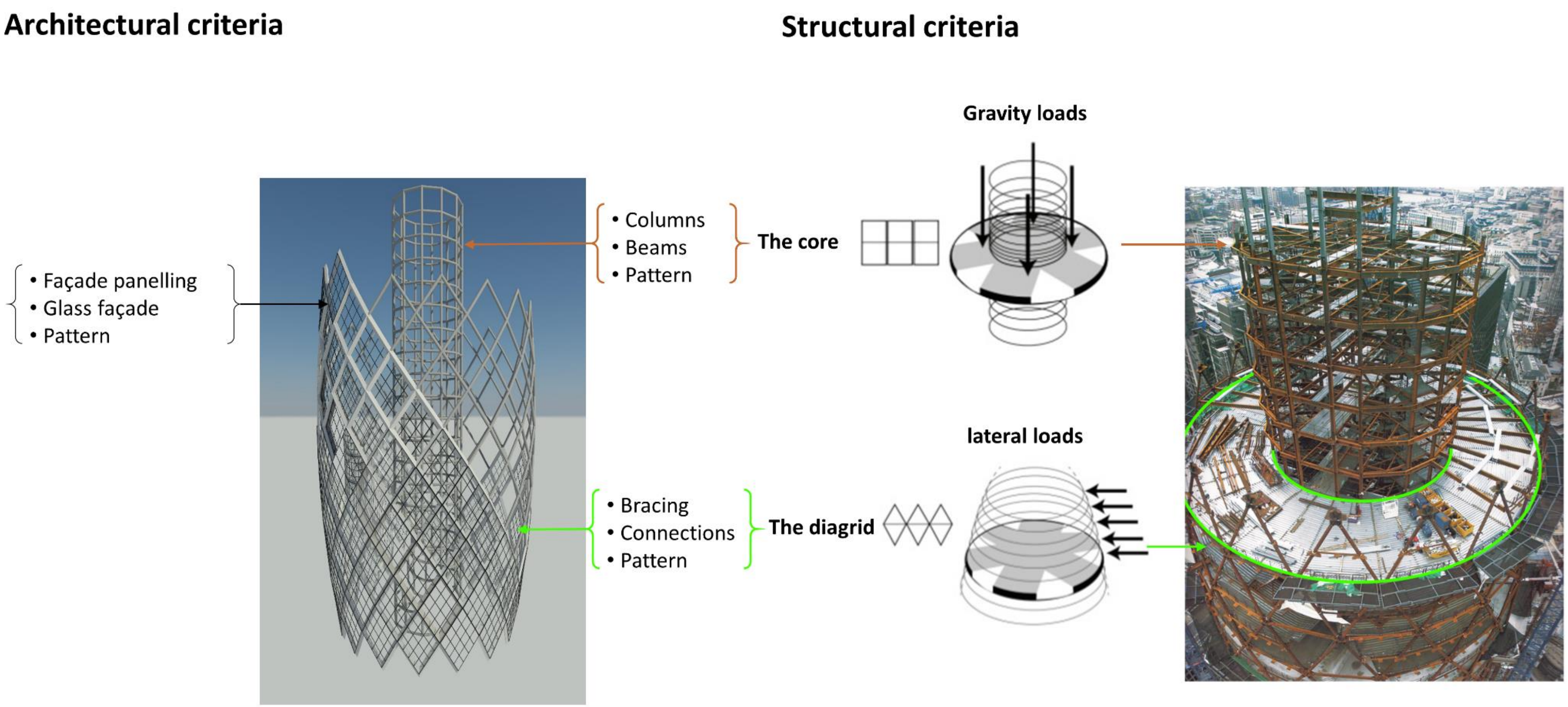


Figure 66: Relationship between architectural and structural design criteria

Shape optimisation

Building shape can affect the architectural aesthetic integrity, structural safety and strength. Therefore, the decision on the shape of a building depends on reaching an agreement amongst architects and structural engineers. The proposed prototype facilitates this by automating the structural design process based on the architectural model (boundary conditions). For instance, to improve the safety and serviceability of tall buildings against strong winds, building shape optimisation at the early architectural design stage is considered as the most efficient method to create a wind-resistant design (Tang et al., 2014). Therefore, the proposed prototype enables the structural engineers and architects to work on a synchronised automatic platform and explore the optimum shape of the building; one that reduces the effect of the wind load on the building and meets the aesthetic requirements. According to Figure 67, the cylindrical shape of the Gherkin Tower allows the wind to move around the building and reduces the effect of the wind, while the cubic shape resists against the wind load.

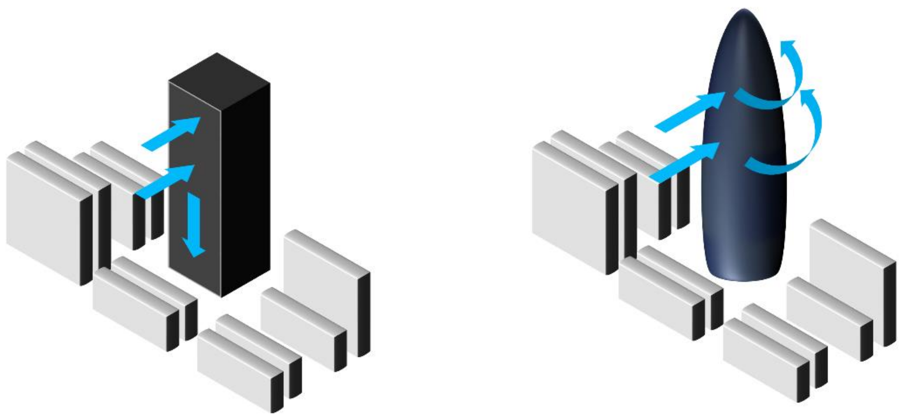


Figure 67: Effect of wind load on the shape of the building

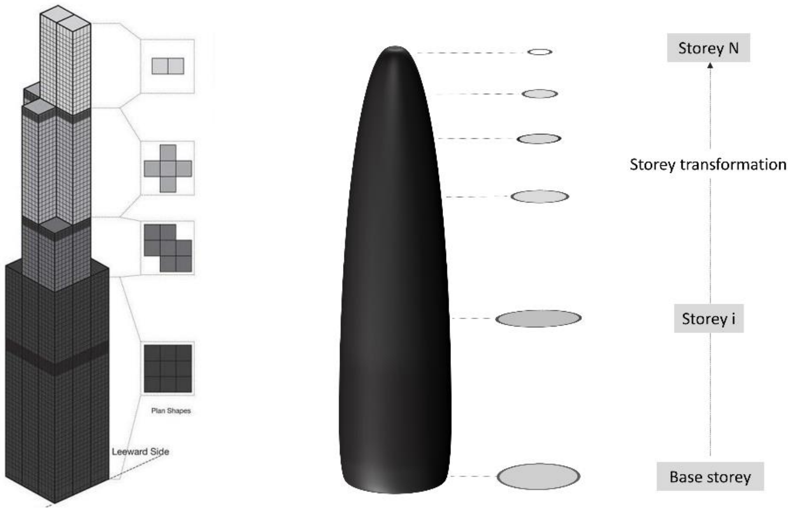


Figure 68: Horizontal and vertical transformation and shape of the building

The proposed prototype enable the designers to modify the building shape parameterisation in two directions – horizontal and vertical. The horizontal direction represents the shape of the floor plan and the area of the building; the vertical direction defines the height of the building. Figure 68 demonstrates two types of horizontal and vertical transformations. The left side tower uses floor plan shapes with a series of squares, where the arrangement of the squares changes along the height of the tower. On the other hand, the right-side tower uses a circle floor base plan shape, where the radius of the circle changes along the height of the tower. The solution proposed here uses this method as a mathematical function in Dynamo to define the shape of the Gherkin Tower by using two variables. The first parameter is the diameter of the circles and second is the level of the centre point of each circle (see Figure 68). Hence, providing various series of circle diameters and circle centre point levels generates different shapes for the tower. Figure 69 demonstrates 4 different options of tower shapes generated by varying the value of parametric variables. All the design options have the same site boundary constraints; they all have the same height of 179 m, the same base floor external diameter of 50 m and the maximum floor external diameter of 56.15 m.

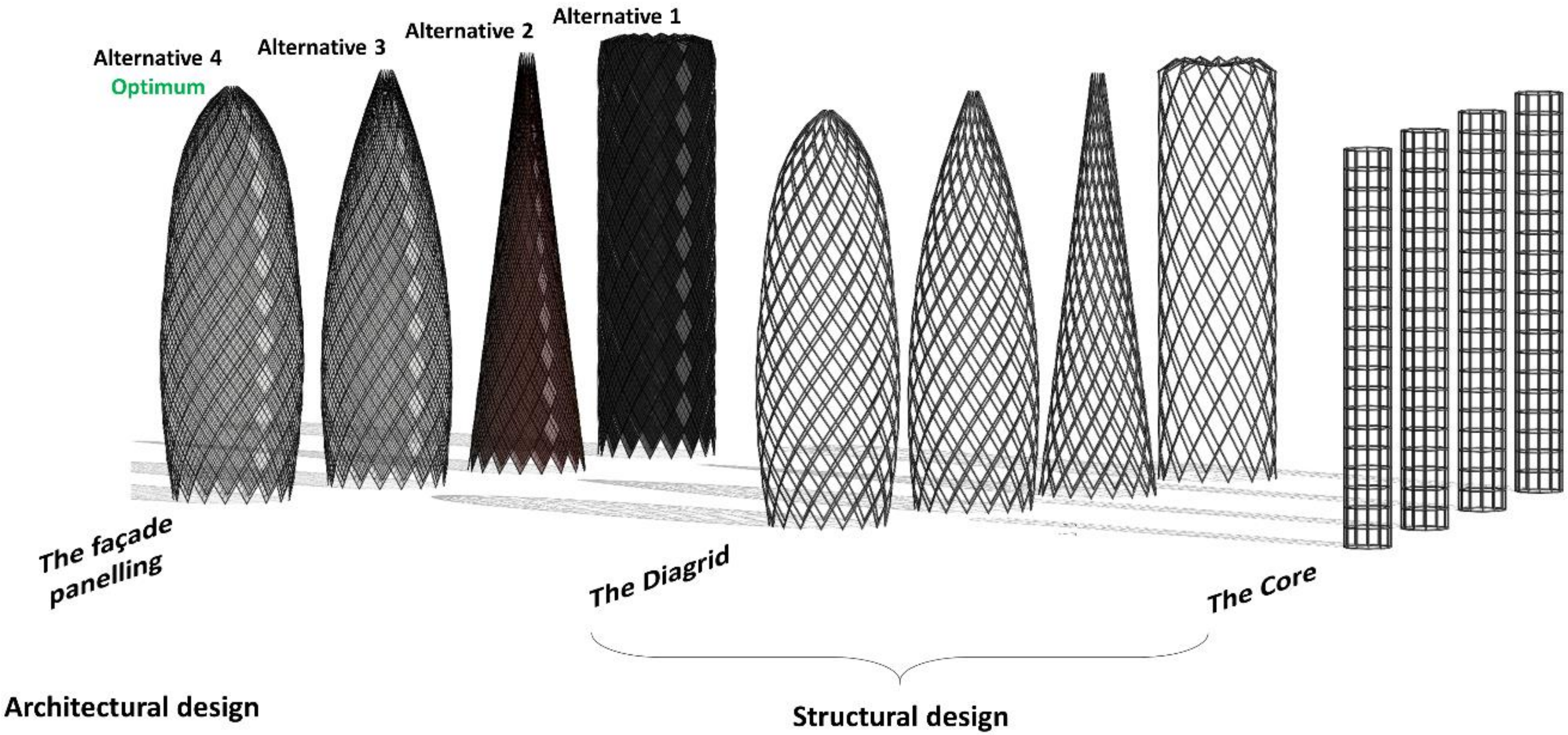


Figure 69: Shape optimisation of the Gherkin tower by using SDO Prototype

Topology and size optimisation

The optimum option of the tower shape with architectural and structural efficiency is adopted and the design proceeds to the structural topology design and optimisation. This prototype defined three different mathematical functions to design the core structure, the diagrid structure and the façade panelling of the tower. Each approach has specific formulations to solve the design problem; it uses specific parametric constraints (design variables) to design different topology options. In this case, the diagrid structure and the architectural façade were designed by using 'quad.diamond panel' node from 'LunchBox Quad by face' package (Johnson, 2016) in Dynamo to create diamond features. In addition, the core structure was designed by using a 'surface panelling' package to create rectangular features. By varying the design variables of each function, the corresponding topology varies. Therefore, different topology design options will be designed and analysed in RSA and the results will be used for optimisation, to choose the best model between different options. Even though design alternatives with more diagrid patterns might be preferable from the structural engineers' point of view, these design alternatives may not be practically and aesthetically desirable for contractors, architects and clients. The density spaced diamond diagrids may reduce the aesthetic value of the building and create a less attractive architectural design. Moreover, the more diagrid diamond pattern may also affect the amount of energy consumption, as it creates blockage for the sunlight penetrating the building and reduces the natural light of the building. This kind of conflict requires constant collaboration and communication between architects and engineers during the design process. Defining an accurate mathematical design function to generate alternative designs helps to speed up the generation of the conceptual design. Moreover, defining appropriate penalty functions helps to exclude the unwanted models from the loop and generate suitable designs. Figure 70 demonstrates four different variations of structural topology designs, which are linked to the architectural façade panelling design.

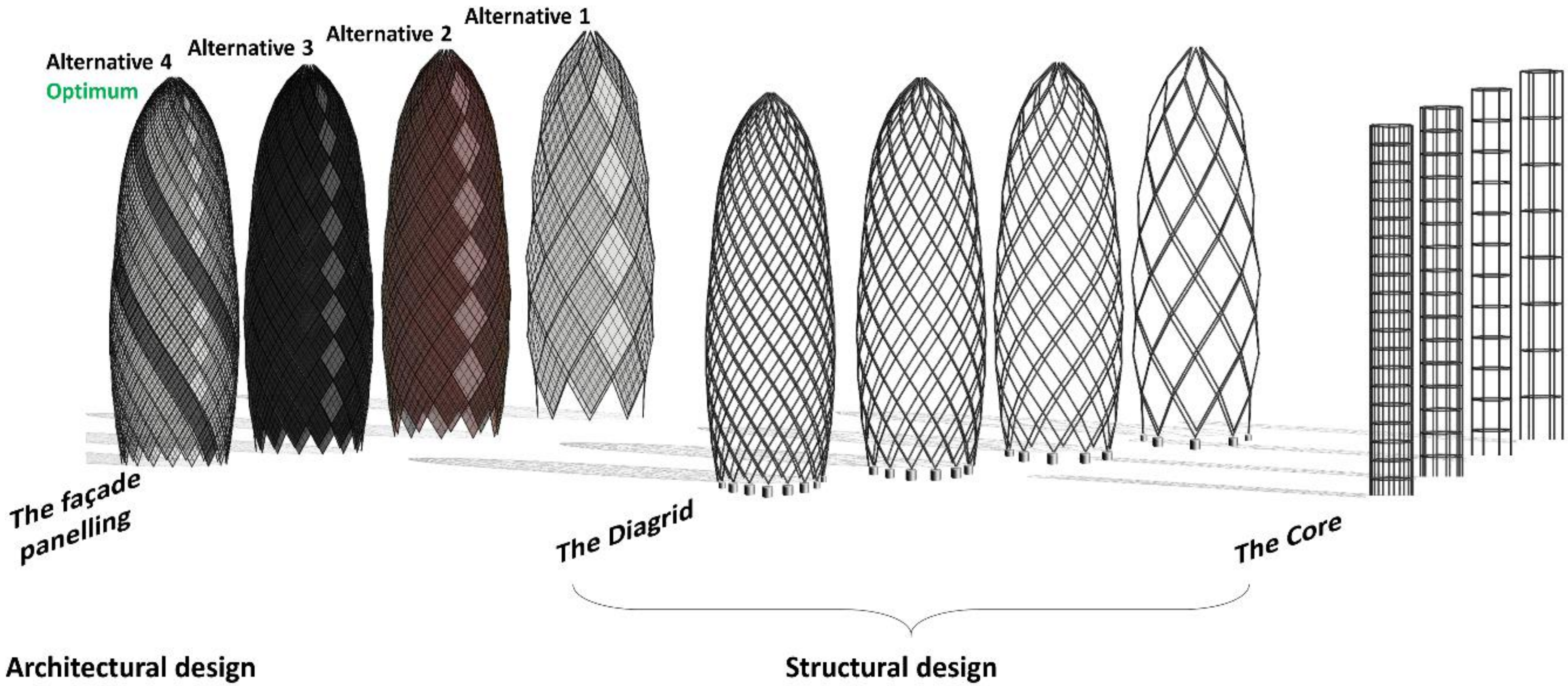


Figure 70: Topology optimisation of the Gherkin Tower by using the SDO Prototype

4.4 Summary

This section presents the process of design and development of the framework and prototype. In this process, based on the findings from the literature review a Conceptual Structural Design and Optimisation (CSDO) framework was developed as a potential solution to the identified challenges during the structural design and optimisation process. Thereafter, an online questionnaire was distributed between professionally accredited structural engineers of IStructE, ICE and ASCE in UK and US to validate the framework. The aim of the questionnaire was to justify the research knowledge gap and provide more potential solutions to solve the gap. The objective of the questionnaire was to explore the existing issues in the conceptual structural design and the optimisation process and to find how the conventional system with BIM can solve the issues. In order to meet these objectives, the questionnaire needed to be designed based on some factors including sample size, type of questions, number of questions, characteristics of the respondents, availability of time, financial implications and ease of data analysis. According to the results received from the data analysis of the responses to the questionnaire, the CSDO framework was modified and the extended version of the Structural Design and Optimisation (SDO) framework was developed. Thereafter, a proof of concept prototype was developed to demonstrate the workability of the framework.

The outcome of the research provides a much-needed toolset and associated procedures to assist in integrating various participants across the design procedure of buildings. The proposed framework and proof of concept prototype offers a workable solution to enhance efficiency and reduce conflicts and clashes that occur as a result of fragmented and silo-based procedures of structural design. The study stands out among similar ones, given that it provides a first-of–its-kind toolset that relies on an automated synergy to use architectural parametric data for the multi-disciplinary optimising of structural design. In the proposed prototype, the use of precise formulation and functions for the automatic structural design and optimisation is the key to obtain a proper solution. An accurate and comprehensive problem formulation should propose the design problem and maintain a high level of accuracy, during the evolutionary design process. In this research, the maximum strength and less self-weight are considered as the objective functions of the optimisation to explore strong and at the same time light steel frame structure design. Therefore, mathematical functions are defined in Dynamo to use different sets of variables to design and analyse different options of the structural model in the Robot Structural Analysis (RSA), comparing the results in terms of strength against the applied loads, self-weight, and eventually propose the best option.

Chapter 5: **Conclusion**

One of the prevalent challenges facing the design professionals, including architects and engineers, is maintaining the flow of information among various disciplines and addressing the competing and frequently conflicting interests (Abrishami et al., 2015; Beghini et al., 2014). This is because, the traditional supply chain in the construction industry displays a lack of integration of these two disciplines (architects and engineers); their working procedures are fragmented, segmented and affected by silo mentality (Durdyev et al., 2019; Mignone et al., 2016). These two groups work in isolation and recognise responsibility, merely for their own portion of work, hence set different priorities. That is, traditionally, the focus of architects is on the aesthetic factor of the building (building shape), while engineers give priority to strength and efficiency of building structures (Hurol, 2014; Vilutiene et al., 2019). Such mindsets have given rise to serious problems: non-productive activities with up to 15% of cost and time overruns; many change orders accounting for between 60%–90% of all variations, and inefficient communications that yield an additional 5%–10% in cost and time overruns (Durdyev et al., 2019; Kraatz, Sanchez, & Hampson, 2014).

Despite the availability of BIM, IPD – and Common Data Environment (CDE) – the gap among architects and structural engineers remains a problem to be addressed (Oraee et al., 2017). The solution, as Merschbrock and Munkvold (2014) and Kassem et al. (2014) argued, relies on developing data exchange frameworks and tools. Developing new tools is recommended as an effective solution to facilitate integrating architectural-structural collaboration (Beghini et al., 2014). Therefore, a comprehensive literature review was conducted to obtain more information about the existing challenges during the structural design and optimisation process and explore potential solutions to solve the problems. Based on the finding from the constant literature review a Conceptual Structural Design and Optimisation (CSDO) framework was conducted. This framework proposed a new process, which uses the architectural data to design alternative structural models. Moreover, Genetic Algorithm (GA) was proposed as a potential algorithm for the structural optimisation process. In order to validate the CSDO framework an online questionnaire was distributed between professionally accredited structural engineers of the IStructE, ICE and ASCE in the UK and US. Data analysis of the online questionnaire provided a valuable information about the existing challenges and potential solutions to address the issues. Therefore, based on the results of the online questionnaire the CSDO framework was amended and the extension version of Structural Design and Optimisation (SDO) Prototype was developed. In order to demonstrate the workability of the prototype it was validated through 10 interviews between academic staff and chartered structural engineers. Furthermore, a focus group was conducted between a research team of Autodesk. The outcome of the research provides a much-needed toolset and associated procedures to assist in integrating various actors across the design procedure of buildings. The proposed SDO Prototype offers a workable solution to enhance efficiency and reduce conflicts and clashes that occur as a result of the fragmented procedures of structural design. The research stands out among similar ones, given that it provides the first of its kind toolset that relies on an automated synergy to use architectural parametric data for multi-faceted optimising of structural design. In this process, software prototyping method was used to develop the SDO Prototype. In this method, the process of development was divided into several stages and at each stage; a basic prototype was developed and evaluated to ascertain their functionality and workability with other stages. As figure 71 and 72 demonstrates, this prototype uses 3 different tools for the design and optimisation processes. The first stage is the integration and synergy between the architectural and structural design, which starts from the architectural model in Revit. At this stage, architectural information are used to define the structural model layout and topology. Structural designs are generated at the second stage, which is performed in Dynamo by using certain nodes and codes. The second stage is the core part of the prototype, which performs the structural design and optimisation and exports the data from the first stage to the third stage. The third stage performs the structural design and Finite Element Analysis (FEA) in Robot Structural Analysis. In this process, RSA designs analyse and save the alternative structural models and results in an already defined directory path file.

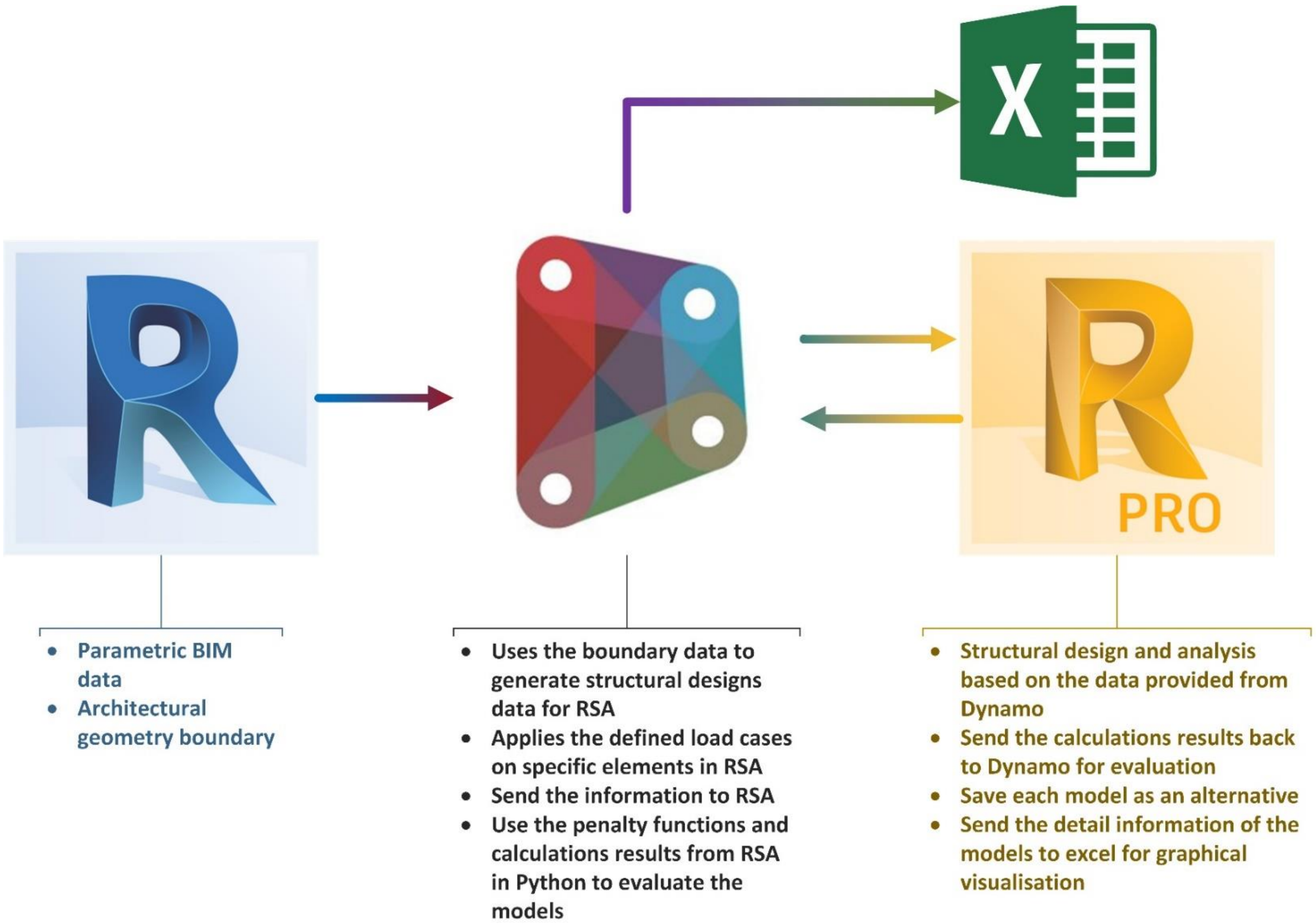


Figure 71: The BIM tools used to develop the SDO Prototype.

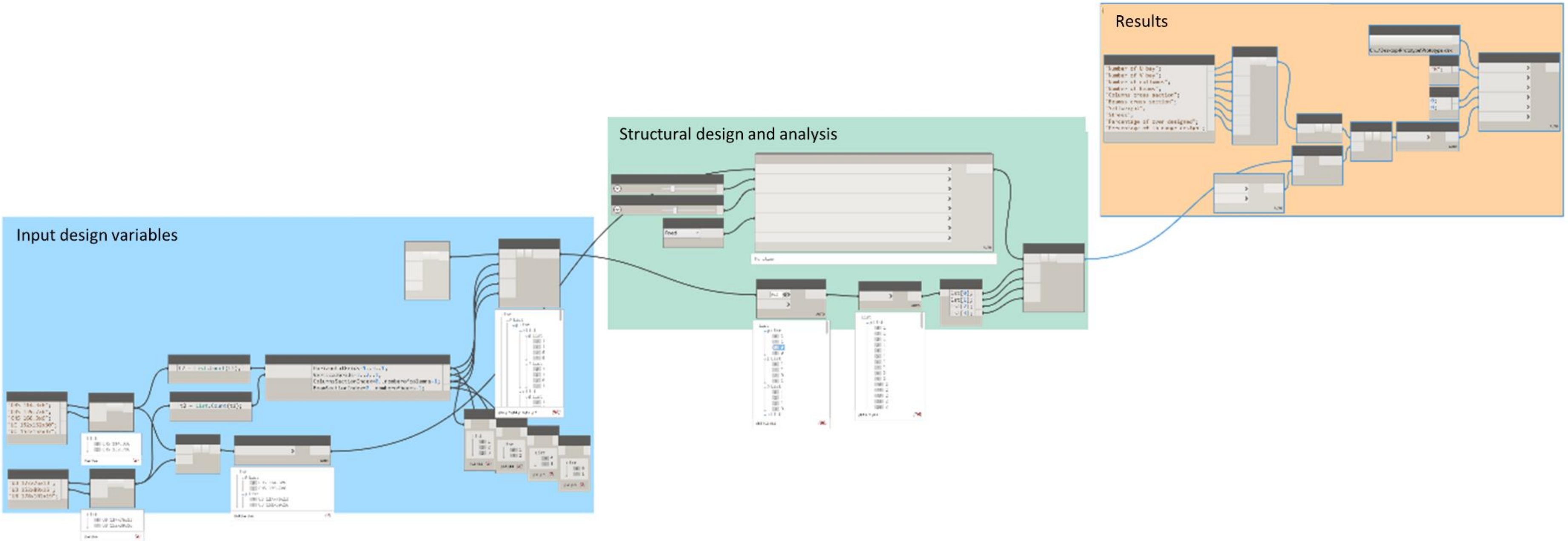


Figure 72: An over view of the SDO Prototype process in Dynamo for the residential building design and optimisation in three steps of input design variables, structural design and analysis and results.

5.1 Theoretical contributions

With the above in mind, the research contributes to the field through extending the outcomes of previous studies that managed to provide optimisation of structural design, albeit in one dimension like shape, topology (Tsavdaridis et al., 2015; Wu and Tseng, 2010) and size (Jalili and Hosseinzadeh, 2018; Hasançebi et al., 2009) in structural design. That is, the prototype here considers all dimensions simultaneously. The research also provides a practical demonstration for researchers who recommended merging architects and structural engineers in one system, making their practices inseparable, to shift from current practices to a fully integrated architectural/structural design system (W Addis, 2007; Billington et al., 2003; Khan, 2004; N. O. Nawari, 2011; Sandaker, 2007; Schueller, 2008).

The research also broadens the boundary of application for previous attempts that focused on structural optimisation of particular structures like truss members (Hasançebi et al., 2009; Kaveh and Ghazaan, 2015; Kaveh and Mahdavi, 2014; Miguel and Miguel, 2012; Dede et al., 2011; Gholizadeh, 2013; Miguel et al., 2013; Degertekin, 2012). The proposed framework and prototype can be rolled over to various types of structures including buildings, as well as infrastructure projects like bridges, trusses high-rise towers, etc.

5.2 Practical contributions

Apart from theoretical contributions, as discussed, the solution provided here would be appealing to the world of practice, particularly for practitioners active in various fields of structural design for different type of structures. The solution will be invaluable, as discussed below.

- This solution enables designers to develop mathematical functions and direct machines to extract what they need from the architectural models, to be used for structural design, based on defined parameters that vary and generate alternative structural design solutions. This gives practitioners great flexibility to customise the system for certain projects, various clients and different demands. As an example, the solution can easily be adjusted for different design codes for steel/ aluminium, timber and RC structure in different regions (see Figure 73).

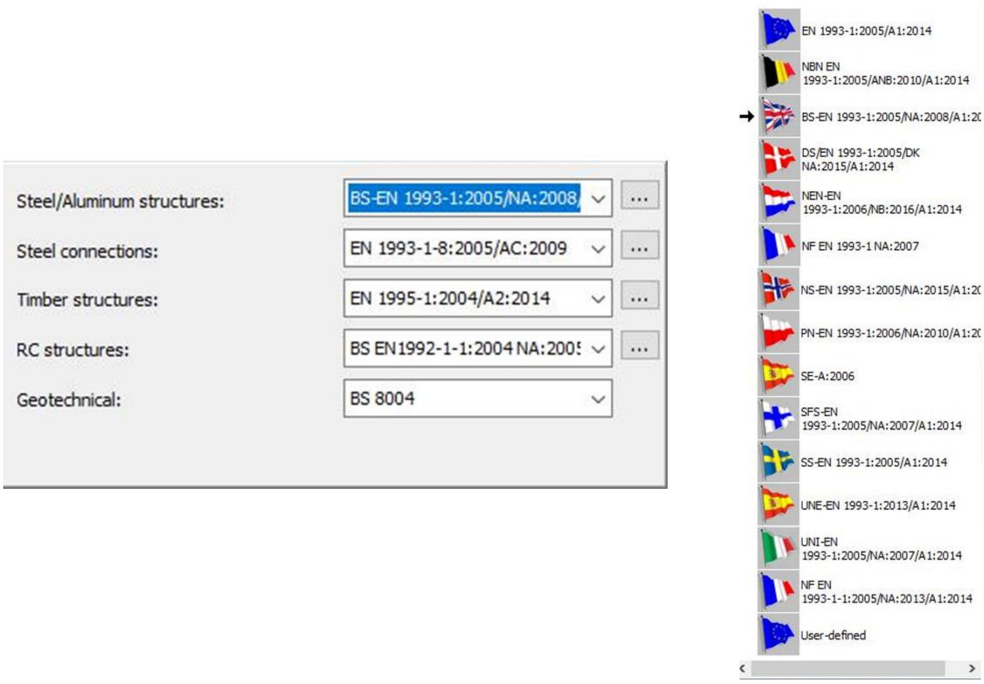


Figure 73: Different design codes in various regions.

- This method provides great efficiency and provides a wide range of alternatives for structural design. Limitation of time and labour and human error prevent designers from exploring all available solutions; the proposed system overcomes these and provides designers with higher efficiency to explore all possibilities within the boundaries of their demands and requirements.

- The prototype relies on common tools and software available to most design practitioners. As such, the solution is cost effective and feasible even for small businesses.

5.3 Future work

Regardless of the contributions to academia and the world of practice, in broad terms, this research promotes the possibilities of shifting from discipline-based design into integrated design – among various disciplines, as another step towards making BIM level 3 happen. This provides a fertile area for research that focuses on improving the idea proposed here through creating user-friendly platforms that automate the procedure based on a set of variables as inputs and creates efficient design alternatives for clients, including structural, MEP, etc.

As another area for further exploration, the experience shared here brings to light the requirements of future design professionals in terms of their knowledge, skills and abilities (KSAs). Future research must explore the necessity of generating a new generation of designers with programming capabilities and including coding programs for construction-related curricula at universities. So too, researchers must target further investigation and development in the RSA API to expand the workability of the prototype for automatic synergy between architectural and structural design, analysis, optimisation and evaluation. The proposed prototype enables the designers to define certain codes to facilitate time consuming and iterative tasks in the structural design process. For example, defining codes for automatic 3D design of pitched roofs in buildings and defining the optimum arrangement of the structural elements, which is a time-consuming process and mainly structural engineers, use their experience and previous successful design in this type of project and rarely search for new methods or optimum solutions. This prototype can be extended and used to explore the best arrangement of the structural elements where different factors can affect the design, and using these factors as design constrain and input data to generate alternative structural design and find the optimum solution. For example, the prototype can be extended to consider the openings in the design and give penalty function to the generated alternative structural designs, which has an element in the architectural openings. Furthermore, this prototype can be improved and extended by using bridge design codes of design and used in iterative structural design tasks in designing bridges. For example, in the design of suspension bridge, this SDO prototype can be used to generate alternative structural bridges with different numbers and sizes of cables, evaluate them based on the most critical factor in the bridge design, and select the optimum solution, which is economic and stable. In addition, this prototype can be used in the design of warehouses, which is a time consuming task, and any change in the design requires the designer to change all the arrangement of the structural elements. SDO prototype is capable to be extended and enable the structural engineers to define the codes once and use them for different projects by adjusting the parametric input data.

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Appendix A

Application for Ethics Review – Staff and Postgraduate Students

1. Study Title and Key Dates

1.1 Title
Optimisation of the conceptual structural design in BIM
1.2 Key Dates
Date of original submission to ethics committee: Version number of original submission: version 2 Ethics Committee Reference Number: TECH 2019 - T.H – 02 Intended Start Date of Data Collection: 10/11/2019 Expected Finish Date of Data Collection: 30/11/2019 *When resubmitting an updated application (e.g. in response to ethical review, or an application for substantial amendment):* Date of resubmission to ethics committee: 25/10/2019 Version number of resubmitted documents: 2

2. Applicant Details

2.1 Principal Investigator	
Name: Tofigh Hamidavi	Title /Role /Course of study: Mr/ Student/ PhD
Department: School of Civil Engineering and Surveying	Faculty: Technology
Telephone: 07507266112	Email: Tofigh.hamidavi@port.ac.uk

Has the principal investigator attended the graduate school (for students) or researcher development programme (for staff) research ethics training session?	Yes 20/10/2017
2.2 Supervisor (if Principal Investigator is a student)	
Name: Sepehr Abrishami Title /Role: Dr/ first Supervisor Department: School of Civil Engineering and Surveying Faculty: Technology Telephone: 02392842905 Email: sepehr.abrishami@port.ac.uk Names and email of any other supervisors: Name: David Begg Title /Role: Dr/ 2nd Supervisor Department: School of Civil Engineering and Surveying Faculty: Technology Telephone: 02392842476 Email: david.begg@port.ac.uk Name: Pasquale Ponterosso Title /Role: Dr/ 3rd Supervisor Department: School of Civil Engineering and Surveying Faculty: Technology Telephone: 02392842932 Email: pasquale.ponterosso@port.ac.uk	
Has the supervisor attended the researcher development programme research ethics training session?	Yes
2.3 Others involved in the work/research including students and/or external collaborators (name, organisation/course, role in the project)	
The data will be collected from the chartered and associate members of the Institution of the Structural Engineers in the UK. The data will be used to validate the Structural Design Optimisation (SDO) framework by using proof of concept prototype.	

3. Details of Peer Review

This research has been successfully passed the major review exam. Please find attached confirmation of approval of my Major Review and therefore registration for the degree of Doctor of Philosophy/Medicine (PhD/MD).

4. Funding Details

Self-funded project.

5. Sites/Locations

The work will take place at the University of Portsmouth. An online interview will be conducted with the people who participated in the previous online questionnaire and showed interest to participate in an online interview. Data will be recorded by taking notes. The results of the data received from the interview will be analysed to validate the framework and prototype. Before the real interview takes place a pilot test will be conducted between BIM and structural engineering lecturer and PhD students at the University of Portsmouth.

6. Insurance/indemnity Arrangements

This research includes normal educational research and doesn't involve any certain kind of activity.

7. Aims and Objectives/Hypothesis

7.1 Aims
This research is aiming to optimise the conceptual structural design process in BIM and improve the synergy between architects and engineers through an automated process of structural design exploration and optimisation. The Structural Design Optimisation (SDO) framework is prepared at this stage of the research, which contain BIM platform, and represent a unique approach to automatically redesign conceptual structural design alternatives and optimise them based on the designers' preferences. The interview aims to validate the SDO framework through a proof of concept prototype.
7.2 Primary Objective
Develop a framework/prototype to improve the conceptual stage of the structural design and synergy between architects and engineers through an automated optimisation process.
7.3 Secondary Objective(s)

- A summary of the early stage structural design process

- Develop conceptual framework based on findings from extant literature review

- Justify and validate the conceptual framework

- Develop the extended framework

- Develop a proof of concept prototype

- Validate the extended framework through the proof of concept prototype in the real settings interviews and focus groups by using case studies

8. Study Summary

8.1 Justification/Summary of Study (no more than one side)
Structural design and analysis is an important and time-consuming process, particularly at the conceptual design stage (Fenves, Rivard, & Gomez, 2000). Decisions made at this stage can have an enormous effect on the entire project, as it becomes ever more costly and difficult to alter the choices made early on in the construction (Larsen & Tyas, 2003; Neale et al., 2016). Hence, optimisation of the early stages of structural design can provide important efficiencies in terms of cost and time. This research suggests a structural design optimization (SDO) framework which automatically generates and optimises alternative structural designs during the early stages. This framework has the potential to leverage conceptual structural design innovation in Architecture, Engineering and Construction (AEC) projects. Moreover, this framework improves the synergy between the architectural stage and the structural stage. It is shown that this SDO framework can make this achievable by generating alternative integrated architectural and structural models based on the extracted parametric BIM data from the architectural model. The proposed SDO framework is justified and validated through online questionnaire. According to the data received from the questionnaire respondents an extended version of the questionnaire and proof of concept prototype are developed. This prototype will be used in interview by using case studies to validate the extended version of the framework and show the workability of the prototype. The target population is the chartered IStructE engineers in the UK who has participated in the past questionnaire and showed interest to participate in the interview. This study uses the advantage of Building Information Modelling/Management (BIM) data, which is one of the promising recent developments in the AEC industry. BIM represents a new paradigm within AEC, one that encourages collaboration of the different AEC roles on the same model, or Common Data Environment (Azhar, 2011).
8.2 Anticipated *Ethical* Issues
1. Confidentiality of participants will be ensured and information collected will be used for the purpose of this study only. No personal details will be collected at any stages of this research. There are no direct benefits to participants or coming from the research. The participants will be

informed that the participation is voluntary and they may withdraw at any stage of data collection. There will be no harms to participants as they will be contacted through emails electronically.

2. Wasting people's time: participants will be informed of the time commitment to contribute in the interview or to complete the questionnaire before proceeding.
3. Personally sensitive information: It is not expected that any part of the interview or the questionnaire effect personally sensitive information. Moreover, respondents will be informed that they may leave the interview or the questionnaire at any stage.
4. Raising expectation: It might be possible that respondents expect to receive benefit from contributing to the interview or the questionnaire. In order to avoid such situation, the respondents will be aware from the beginning of the interview or the questionnaire that they wouldn't receive any benefit for their contribution.
5. Potential for sharing confidential information: The respondents will be informed from the beginning that the data and information they share during their contribution will not be shared with others and they will be permitted to opt-out of any enquiries they feel uncomfortable with.
6. Participants will receive an information sheet explaining the use of their information, data storage, how we maintain anonymity.

8.3 Anticipated other *Risks or Concerns*

Risks to participants: The only risk to participants is that the research will take some of their time to participate in the interview or the questionnaire.

Risks to researchers/ university staff/students: The research does not require lab, chemical staff and equipment, also the research doesn't need travelling to any new place for the purpose of data collection.

Reputational risks: This research does not have any reputation risks. In the worst situation if the research wouldn't be able to provide an efficient framework, it would be useful and comprehensive source contributes to knowledge in terms of conceptual structural design optimisation process in BIM.

Security risks: None

Other: None

8.4 Medical Cover (if applicable)

N/A

9. Description of Method/ Protocol

In order to have a better understanding of the gap and related factors, along with the literature review, semi-structured interview and questionnaire will be provided. Questionnaire would be one of the methods to evaluate the conceptual framework. Semi-structured interview is another useful method will be used to explain the conceptual SDO framework in details to the participants and validate the framework based on the responses.

Interview can help to collect the fresh, new and primary information as needed. Sufficient information can be collected through the interview process. Any misunderstanding and mistake can be corrected easily in an interview. Because the interviewer can ask any question to the interviewee. To explore more or to find out the actual reasons behind the research gap interview method can be efficient method. In this scenario, semi-structured interview will be used because this approach provides several key questions which help to define the areas to be explored, but also allow the researcher the flexibility to pursue the research in more detail. The main disadvantage of the interview is the cost of this method, therefore, online interview format will be used through skype or any other application which is more convenient for the participants.

Questionnaire is a quick way to collect various data from many people at once which is easy to classify and analyse. The questionnaire will be delivered electronically by using Google forms. Before distributing the questionnaire, it will be tested through pilot studies. For the pilot test, the questionnaire will be sent to the civil engineering lecturers at the University of Portsmouth. Thereafter, the questionnaire will be troubleshoot and improved based on the feedbacks received from the participants.

The interview includes two sections as explained below:

Section 1: About the interview

This section provides brief explanation about the research, purpose of the interview and confidentiality to the interviewees.

Section 2: Interview questions

This section is the main part of the interview, which includes the interview questions. The type of the questions are semi-structured questions starts with quantitative questions and finishes with the validation of the framework through qualitative questions (please see the PDF version of the interview at the end of this document). This section begins with explaining how the framework solve the current challenges in the structural design and optimisation process and synergy between architects and engineers through an automatic process. Thereafter, the prototype shows the workability of the framework through a proof of concept prototype by using case studies. Thereafter, the respondents will be asked about their views of the proposed prototype. This section helps to justify the knowledge gap and validate the framework and prototype.

(Please see the link to the online questionnaire or PDF version file at the end of this document).

10. Compliance with Laws, Codes, Guidance, Policies and Procedures

The researcher will comply with the following documents:

- The University of Portsmouth Ethics Policy.
- The University of Portsmouth Research Data Management Policy and associated retention schedules.
- Guidance on conducting research in your own place of work.

- The Research Councils UK Policy and Guidelines on Governance of Good Research Conduct.
- The Research Councils UK Concordat for Engaging the Public with Research
- The UK Research Integrity Office Code of Practice for Research

11. Recruitment of Participants

11.1 Who are the Research/ Participant Population?

The population size are the professionally accredited structural engineers in the Institution of Structural Engineers (IStructE) in the UK, who participated in the previous online questionnaire and showed interest to participate in an online interview.

11.2 Inclusion/Exclusion Criteria

Inclusion Criteria: Participant would be chartered engineers registered in the IStructE.

Exclusion Criteria: Participants who are not IStructE members.

11.3 Number of participants (include rationale for sample size)

The size of the sample is limited to the size of your interviewing staff, the area in which the interviews are conducted, and the number of qualified respondents within that area (DeFranzo, 2014). The number of participants in the previous online questionnaire who showed interest to participate in the interview are 58 people. The interview will continue until almost the same results will be received from the participants, but the number of the interviews will not be more than 15.

For the questionnaire, the confidence level of 95% is assumed. Additionally, considering time and accuracy of results margin of error 10% is assumed. Therefore, having the population size of 6908 gives a sample size of 364. This number means at least 364 surveys need to be sent out to have a representative sample for this research.

11.4 Recruitment Strategy (including details of any anticipated use of a gatekeeper in host organizations to arrange/distribute participant invitations)

The researcher will uses professional Architecture, Engineering and Construction (AEC) networks, such as CNBR, ARCOM, IStructE, and LinkedIn. In order to assure that the respondents are meeting the research criteria, they will be asked to identify their formal recognition of professional status as a member of IStructE within the questionnaire, and non-member responses will be excluded. A similar recruitment strategy to the questionnaire will be used to arrange semi-structured interviews and approach the targeted population. Also, respondents to the questionnaires will be asked if they are interested to be involved in the semi-structured interview.

11.5 Payments, rewards, reimbursements or compensation to participants

Participants will be informed that contribution to the research is voluntary and without recompense. Participants will be thanked for the time they provide to answer the survey.
11.6 What is the process for gaining *consent* from participants?
The consent form will be sent along with the questionnaire through email to the participants (who are chartered members in the IStructE). Regarding the interviews, the consent will be taken from the participant by using the prepared consent form which has been attached to this application. Therefore, a completed and returned survey questionnaire can be considered as implied consent, and also a formal written consent is provided.
11.7 Has or will consent be gained from other organisations involved (if applicable)?
N/A
11.8 Arrangements for translation of any documentation into another language (if applicable)?
N/A
11.9 Outline how participants can withdraw consent (if applicable), and how data collected up to this point will be handled. Also stop criteria for specific tests (if applicable)?
The interview and the questionnaire will be started by informing the participants that they are free to withdraw from the study at any time if they decide not to continue. If the participant does withdraw from the survey after some information have been collected, then the participant will be asked if he/ she is content with the information collected so far to be retained and included in the study. If the participant prefers the data collected can be destroyed and not included in the study. However, once the research has been completed and the data analysed, it will not be possible for the participants to withdraw their information from the study.
11.10 Outline details of re-consent or debrief (if applicable)?
N/A

12. Data Management

12.1 Description of data analysis
This research will have quantitative and qualitative data which needs to be analysed. The qualitative data will be analysed by using NVIVO, and quantitative data will be analysed using SPSS software. Regarding the questionnaire, the data from the questionnaire will be imported to SPSS for analysing the category of participants such as number of year experience, number of BIM participated projects. However, the responses of participants will be analysed as Qualitative Content Analysis through coding, Conceptualisation, classifying, categorising, identifying themes, and Interpretation, creating explanatory

accounts. And the result of this analysis will be articulated as intensive literature review in order to justify the research and modify the conceptual SDO framework. Regarding the Interview, the conceptual SDO framework will be evaluated. The data from the interview will be analysed in NVIVO. The analyzing process should be organized to avoid missing the data. The analyzing process begins by organizing the data by coding through two stages, first, gather the similar data meaning in one unit, second arrange and code the organized data. After that, check the validation of these data and the relevance of the main questions. The type of the questions are semi-structured questions starts with quantitative questions and finishes with the validation of the framework through qualitative questions.
12.2 Where and how will data be stored?
For the data storage, Google form, Nvivo and N-drive at the University of Portsmouth system will be used.
12.3 Destruction, Retention and Reuse of Data
This process will follow university regulations regarding reuse the collected data, as well as, the consent form which will be signed by the participants includes specific clauses to manage how the collected data can be used in other research purposes. The UoP will be responsible for managing and retaining the data after the researcher leaves the university, the period is ten years in accordance with UoP regulations. In terms of the consent forms, the researcher will retain them for ten years after collecting them, after that, the researcher will destroy them.
12.4 Personal Data – How will confidentiality be ensured (for instance will anonymisation be used)?
No personal data of the participants will be required in this research. Additionally, the collected data will anonymously be saved in the University of Portsmouth system and will be accessible only to authorised personnel of the University.
12.5 How will organisational data (publically unavailable data) be handled (if applicable)?
The study does not include organizational data.
12.6 How will security sensitive data be handled (if applicable)?
N/A

13. Publication / Impact / Dissemination Plans

No publication plans yet. In the case of publishing, research publications will be Open Access (OA).

14. References

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Neale, M. C., Hunter, M. D., Pritikin, J. N., Zahery, M., Brick, T. R., Kirkpatrick, R. M., . . . Boker, S. M. (2016). OpenMx 2.0: Extended structural equation and statistical modeling. Psychometrika, 81(2), 535-549.

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Larsen, O. P., & Tyas, A. (2003). *Conceptual structural design: bridging the gap between architects and engineers*: Thomas Telford.

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Triangle, T. A. (2016). TYPES OF INTERVIEWS FOR DATA COLLECTION. from https://researcholic.wordpress.com/2016/02/18/types_of_interviews/

15. Appendices

Put N/A in version Number column if necessary		
Document	Date	Version No.
Application Form	29/08/2019	3

	Invitation Letter	25/04/2018	1	
	Participant Information Sheet(s) (list if necessary)	29/03/2018	1	
	Consent Form(s) (list if necessary)	29/03/2018	1	
	Supervisor Email Confirming Application	14/05/2018	1	
	Questionnaire	01/02/2018	1	
	Interview Questions / Topic List	05/09/2019	1	

16. Declaration by Principal Investigator and Supervisor (if applicable)

16. Declaration by Principal Investigator and Supervisor (if applicable)

1. The information in this form is accurate to the best of my/our knowledge and belief and I/we take full responsibility for it.

2. I/we undertake to conduct the research/ work in compliance with the University of Portsmouth Ethics Policy, UUK Concordat to Support Research Integrity, the UKRIO Code of Practice and any other guidance I/we have referred to in this application.

3. If the research/ work is given a favourable opinion I/we undertake to adhere to the study protocol, the terms of the full application as approved and any conditions set out by the Ethics Committee in giving its favourable opinion.

4. I/we undertake to notify the Ethics Committee of substantial amendments to the protocol or the terms of the approved application, and to seek a favourable opinion before implementing the amendment.

5. I/we undertake to submit annual progress reports (if the study is of more than a year's duration) setting out the progress of the research/ work, as required by the Ethics Committee.

6. I/we undertake to inform the Ethics Committee when the study is complete and provide a declaration accordingly.

7. I/we am/are aware of my/our responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data, including the need to register, when necessary, with the appropriate Data Protection Officer. I/we understand that I/we am/are not permitted to disclose identifiable data to third parties unless the disclosure has the consent of the data subject.

8. I/we undertake to comply with the University of Portsmouth Data Management Policy.

9. I /we understand that records/data may be subject to inspection by internal and external bodies for audit purposes if required.

10. I/we understand that any personal data in this application will be held by the Ethics Committee, its Administrator and its operational managers and that this will be managed according to the principles established in the Data Protection Act 1998 (and after May 2018, the General Data Protection Regulation).

11. I understand that the information contained in this application, any supporting documentation and all correspondence with the Ethics Committee and its Administrator relating to the application:

- Will be held by the Ethics Committee until at least 10 years after the end of the study
- Will be subject to the provisions of the Freedom of Information Acts and may be disclosed in response to requests made under the Acts except where statutory exemptions apply.
- May be sent by email or other electronic distribution to Ethics Committee members.

12. I/we understand that the favourable opinion of an ethics committee does not grant permission or approval to undertake the research/ work. Management permission or approval must be obtained from any host organisation, including the University of Portsmouth or supervisor, prior to the start of the study.

Principal Investigator.. **Date**..15/05/2018

Supervisor (if applicable).. **Date**..15/05/2018

Major Review Confirmation

Memorandum

Date: 28 March 2018

To: Tofigh Hamidavi

CC: Sepehr Abrishami Shokooh
Christina Hampson

From: Melissa Howells, Faculty Advisor, Research Degrees, DSAA

Re: Major Review

I am pleased to confirm approval of your application for Major Review, following the Review Meeting with your assessors. Your registration has been confirmed for the award of PhD.

Your mode of study is full-time and thesis submission will be expected by 31/01/2020. If your First Supervisor agrees, you may submit your thesis at an earlier date to the Research Section, Academic Registry. These dates do not relate to any funding you may receive.

If you require further time beyond your current submission deadline you will need to arrange an extension by completing form UPR12, *Application for Extension of Registration*, re-register and pay extension fees. The form is available at http://www.port.ac.uk/registry/researchdegrees/forms/.

If you have any questions regarding the final examination process, (or any other regulatory or procedural issues which may arise) do contact me and I will be pleased to assist.

Yours sincerely,

Melissa Howells
Faculty Advisor (Research)

Invitation to Questionnaire

University of Portsmouth
School of Civil Engineering and Surveying
Portland Building
Portland Street
Portsmouth
PO1 3AH

+44 (0)23 9284 2918
sces-admin@port.ac.uk

Researcher: Mr Tofigh Hamidavi
Supervisor: Dr Sepehr Abrishami

Survey Questionnaire

Study Title: Optimisation of the conceptual structural design in BIM

FEC Ref No: (if applicable)..........................

Name of researcher and supervisor: Mr Tofigh Hamidavi, Dr Sepehr Abrishami

Contact details: Refer to the letter head which includes necessary information.

Invitation

Thank you for reading this. I would like to invite you to take part in my research study by completing this questionnaire. My research focuses on developing a framework for the automation/optimisation of the conceptual structural design at the early stages of the structural design process. This framework uses Building Information Modelling/Management (BIM) technologies as the central conduit. So far, a conceptual Structural Design Optimisation (SDO) framework has been developed which requires validation, troubleshoot and improvement to develop the extended version of the SDO framework, followed by the working prototype**.**

Please be assured that no personal information will be collected, I neither need your name nor any identifying details; the questionnaire can be completed anonymously and all reasonable steps will be taken to ensure confidentiality. I will ask you for some biographical details [*e.g.* highest degree, subject area, expertise field, years of experience] to help us produce summary statistics, but these will not be used in any attempt to reveal your identity. Responses from completed questionnaires will be collated for analysis; once this is complete the original questionnaires will be retained until completion of the research.

Questionnaire

Link to the questionnaire

Optimisation of the structural design in Building Information Modelling (BIM)

Study Title: Optimisation of the conceptual structural design in BIM
FEC Ref No: 1
Name of researcher and supervisor: Mr Tofigh Hamidavi, Dr Sepehr Abrishami
Contact details: Refer to the letter head which includes necessary information.

Invitation
Thank you for reading this. I would like to invite you to take part in my research study by completing this questionnaire. My research focuses on developing a framework for the automation/optimisation of the conceptual structural design at the early stages of the structural design process. This framework uses Building Information Modelling/Management (BIM) technologies as the central conduit. So far, a conceptual Structural Design Optimisation (SDO) framework has been developed which requires validation, troubleshoot and improvement to develop the extended version of the SDO framework, followed by the working prototype.

Please be assured that no personal information will be collected, I neither need your name nor any identifying details; the questionnaire can be completed anonymously and all reasonable steps will be taken to ensure confidentiality. I will ask you for some biographical details [e.g. highest degree, subject area, expertise field, years of experience] to help us produce summary statistics, but these will not be used in any attempt to reveal your identity. Responses from completed questionnaires will be collated for analysis; once this is complete the original questionnaires will be retained until completion of the research.

Participation in the questionnaire is voluntary and you are free to withdraw from the study at any stage of data collection. I would suggest that completing the questionnaire form should take about 10 minutes. Please feel free to talk to others about the study if you wish.

The questionnaire includes three sections:
1. Demographic Information: Asking about your highest degree, subject area, expertise field, years of experience
2. Structural Design and Analysis: Asking about the current challenges and tools in conventional structural design
3. Building Information Modelling/ Management (BIM): Asking about your knowledge about BIM, current challenges in BIM and tools during the early stage and asking your opinion about the methods used in this research to optimise the structural design during the early stage by using BIM.

If you wish to learn more about the results of the research please write down your email at the last part of the section 5.

Demographic Information

This section asks questions about you. This information is necessary to analyse the data. The data you share with us will not be passed on to anyone else, and will not be used for any other reason.

1. **What is the highest degree you have completed?**
Mark only one oval.

- ◯ Some college, no degree
- ◯ Undergraduate level (e.g. BSc, BEng, etc.)
- ◯ Postgraduate level (e.g. PhD, MSc, MEng, PGC, PGD, etc.)
- ◯ Professional degree (e.g. MD, DDS, DVM)?

2. **What is your expertise field?**
Tick all that apply.
- [ ] Structural engineer
- [ ] Civil engineer
- [ ] Structural design/ analysis software technician
- [ ] Industrial engineer
- [ ] Project manager
- [ ] Construction engineer
- [ ] Surveyor
- [ ] Architect
- [ ] Other: ____________________

3. **What is your area of expertise?**
Tick all that apply.
- [ ] Residential buildings
- [ ] High-rise building
- [ ] Industrial structure
- [ ] Bridge
- [ ] Tunnel
- [ ] Other: ____________________

4. **How many years experience do you have in your area of expertise?**
Mark only one oval.
- ( ) Less than one year
- ( ) 1-5 years
- ( ) 6-10 years
- ( ) 10+ years

5. **What is your formal recognition of professional status as a member of Institution of Structural Engineers (IStructE)**
Mark only one oval.
- ( ) Student Member
- ( ) Graduate Member
- ( ) Technician Member - TIStructE
- ( ) Associate-Member - AMIStructE
- ( ) Associate - AIStructE
- ( ) Chartered Member - MIStructE
- ( ) Fellow - FIStructE
- ( ) Other: ____________________

Structural Design and Analysis

Structural design process include several stages starting with: 1. Conceptual structural design (designer can choose the best design among alternative designs) 2. Detailed structural design (the chosen design in the last stage will be detailed and improved for further analysis) 3. Structural analysis (the detailed structural design will be analysed and optimised to be stable and economical) 4.

Structural design automation (Helps the engineer to design the most optimised design by spending less time and cost).

6. How would you rate your knowledge of the following items?(1: Minimum and 5: Maximum)

Mark only one oval per row.

	1	2	3	4	5
Conceptual Structural Design	◯	◯	◯	◯	◯
Detailed Structural Design	◯	◯	◯	◯	◯
Structural Analysis	◯	◯	◯	◯	◯
Structural Optimisation	◯	◯	◯	◯	◯
Structural Design Automation	◯	◯	◯	◯	◯
Generative and/or Parametric Design	◯	◯	◯	◯	◯
Interoperation with other disciplines	◯	◯	◯	◯	◯

7. Which stage(s) of the structural design process do you think need more improvement?

Tick all that apply.

- ☐ Conceptual Structural Design
- ☐ Detailed Structural Design
- ☐ Structural Analysis
- ☐ Structural Design Automation
- ☐ Structural Design Optimisation
- ☐ Interoperability with other disciplines
- ☐ Other: ______________________

8. Can you list any specific problem(s) in regards to the selected stage(s) in previous question?

____

____

____

____

____

9. Do you have any suggestion(s) to solve the problem?

____

____

____

____

____

10. **How do you generate alternative conceptual structural design during the early stage?**

11. **How helpful do you think having a system for generating alternative conceptual structural designs would be to choose the best structural design among alternatives during the early stage of the structural design?**
Mark only one oval.

	1	2	3	4	5	
Not helpful	◯	◯	◯	◯	◯	Very helpful

12. **Do you think automation in the structural design and analysis can improve designers' capabilities during the early stage?**
Mark only one oval.

◯ Yes
◯ No
◯ Maybe

13. **How would you rate your levels of proficiency related to Computer Skills in structural design?**
Mark only one oval.

	1	2	3	4	5	
No experience	◯	◯	◯	◯	◯	Very expert

14. **Please rate your use of computer tools at each stage of structural design and analysis process**
Mark only one oval per row.

	Not at all	To some extent	Intermediate	Advanced
Conceptual structural design	◯	◯	◯	◯
Detailed structural design	◯	◯	◯	◯
Analysis of the structural design	◯	◯	◯	◯
Optimisation of the structural design	◯	◯	◯	◯

15. **Which one of the following questions reflect your opinion of the issues raised below?**
Mark only one oval per row.

	Yes	No	Maybe
Do you strucggle with using computer tools during the early stage of the structural design?			
Do you struggle interoperating with architectural design?			
Do you struggle designing complicated structures using computer tools?			
Do you spend lot of time finding alternative structural designs?			
Do you spend lot of time to optimise your conceptual structural design?			

16. **Identify the following structural design and analysis software based on your proficiency level.**
Mark only one oval per row.

	Not at all	To some extent	Novice	Intermediate	Advanced
Dlubal RFEM & Dlubal RSTAB					
Sap 2000					
STAAD.Pro					
RISA-3D					
ETABS					
Skyciv 3D Structural Analysis Software					
SCIA Engineer					
Robot Structural Analysis Professional					
Revit					
Tekla Structure					
Advance Steel					
Bentley					

17. **Identify the following structural design and analysis software based on their usability**
Tick all that apply.

	conceptual structural design	Detailed structural design	Structural analysis	Interoperability with other desciplines	Optimisation of the structural design
Dlubal RFEM & Dlubal RSTAB	☐	☐	☐	☐	☐
Sap 2000	☐	☐	☐	☐	☐
STAAD.Pro	☐	☐	☐	☐	☐
RISA-3D	☐	☐	☐	☐	☐
ETABS	☐	☐	☐	☐	☐
Skyciv 3D Structural Analysis Software	☐	☐	☐	☐	☐
SCIA Engineer	☐	☐	☐	☐	☐
Robot Structural Analysis Professional	☐	☐	☐	☐	☐
Revit	☐	☐	☐	☐	☐
Tekla Structure	☐	☐	☐	☐	☐
Advance Steel	☐	☐	☐	☐	☐
Bentley	☐	☐	☐	☐	☐

18. **Do you use other structural design packages? If so please identify your level of proficiency and the stage you use the software.**
Example: LUSAS, Intermediate, Structural analysis

____

19. **Identify your level of awareness and skills proficiency in Building Information Modelling (BIM) tools**
Mark only one oval.

- ◯ No Knowledge/ skills of BIM
- ◯ Aware of BIM, but do not use
- ◯ Aware of BIM, and currently use
- ◯ Expert in BIM

Building Information Modelling (BIM)

20. **Based on your experience in BIM, how would you identify the current challenges at the conceptual structural stage (before the detailed stage)?**
Mark only one oval.

- ◯ Does not support at all.
- ◯ Support challenges but doesn't support the conceptual design
- ◯ Support the conceptual design stage to some extent.
- ◯ Support the early design stage.
- ◯ Supports all the aspects of the early design stage.
- ◯ Not sure
- ◯ Other: ________________

21. **Identify your level of awareness and skills proficiency in Generative Design.**
Mark only one oval.

- No Knowledge/ skills of Generative Design
- Aware of Generative Design, but do not use
- Aware of Generative Design, and currently use
- Expert in Generative Design

22. **Do you think integration of Generative Design and BIM at the early stage of structural design can improve designers' capabilities?**
Mark only one oval.

- Yes
- No
- Maybe
- Other: ____________________

23. **Concerning the integration of BIM and Generative Design, please rank your level of agreement with the following statement**
Mark only one oval per row.

	Strongly disagree	Disagree	Not sure	Agree	Strongly agree
BIM is the future of building design and project information					
Generative Design has a strong potentioal to become a vital computational design paradigm					
Adoption of Generative Design enables the designers to create complex designs easier					
Integration of Generative Design and BIM can improve the conceptual design					
BIM is a better option than the conventional systems for the integration Generative Design into a modelling system					

24. **Do you think automation in the structural design and analysis in BIM can improve designers' capabilities during the early stage?**
Mark only one oval.

- Yes
- No
- Maybe

25. **Indicate which one of the following systems has the potential for the integrating with Generative Design**
Tick all that apply.

- [ ] Autodesk Revit
- [ ] Autodesk Robot
- [ ] Advance Steel
- [ ] Tekla
- [ ] Other: ____________________

Thanks for your contribution in the survey

26. **Please supply your name and contact details (if you would like to receive a copy of the survey results)**

27. **Please supply a list of name and contact details of people you consider an expert in this area, who might like to participate in this survey**

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Google Forms

Interview

Request for interview

Title: Automatic prototype for the optimisation of the structural design at the early stage by using BIM

Dear …………,

My Name is Tofigh Hamidavi; I am a PhD Candidate at the School of Civil Engineering and Surveying at the University of Portsmouth.

I am conducting research to develop a new prototype on Building Information Modelling (BIM) to use the architectural model, extract the required information such as boundary conditions and design and analysis different structural models automatically based on the structural engineers' requirements such as type of cross-sections and potential location of the structural elements. My prototype helps to reduce the time, cost and effort during the iterative process of the structural design and improve the collaboration between architects and engineers during the early stage. Moreover, this prototype provides different potential structural models based on the single architectural model that helps the engineers to optimise the structural model.

As a recognised structural engineer, I would like to invite you to participate in my research and evaluate my prototype. It starts with a short interview about the attached video, which demonstrates the workability of the developed prototype. The interview can be either face-to-face or via Skype and will take approximately 15 minutes. In this interview, I will explain the prototype in details and you will be asked a few questions about it.

Your views on structural design and collaboration of the prototype with architectural models are highly important for this study and are very important for this research so your help will be greatly appreciated.

Your opinion will be anonymised for reporting and will only be used for academic research. Your participation is voluntary but I would be grateful if you could participate.

Looking forward to hearing from you.

Sincerely yours,

Tofigh Hamidavi

Email: Tofigh.hamidavi@port.ac.uk

Skype: Tofigh.h91

Supervisors: Dr Sepehr Abrishami

Interview questions:

Title: Optimisation of the structural design prototype evaluation questionnaire

In-depth questions

1. What do **you think** about the prototype/framework?
2. What did **you like more** about this prototype/framework?
3. Does the prototype/framework **facilitate the structural design** process?
4. Do you think the prototype/framework **follow a logical order**?
5. Is the process of evaluating and comparing **different models clear**?
6. Do you think we can use it for **decision making at early stage** to select the best design?
7. Would you like to **learn** and **use** it in your projects?
8. What are the **barriers** to adopt this prototype/framework in industry?
9. What would you **change** in this prototype/framework to improve it?
10. In **general**, does the system create **positive impact** in structural design process?

---

11. Do you have any further information than you would like to share to improve my prototype?
12. Do you have any questions?
13. Do you like to participate in my future work related to the framework development in automatic design and Optimisation?

Participation Information Sheet

PARTICIPANT INFORMATION SHEET

Title of Project: Optimisation of the conceptual structural design in BIM environment

Name and Contact Details of Researcher(s): Tofigh Hamidavi (Tofigh.hamidavi@port.ac.uk)

Name and Contact Details of Supervisor (if relevant): Dr Sepehr Abrishami (sepehr.abrishami@port.ac.uk)

Ethics Committee Reference Number: ...

1. Invitation

I would like to invite you to take part in my research study. Joining the study is entirely voluntarily. Before you decide, I would like you to understand why the research is being conducted and what would it be expected from you. I will go through this information sheet with you, to help you decide whether or not you would like to take part and answer any queries you may have. I would suggest this should take about 10 minutes. Please feel free to talk to others about the study if you wish. Do ask if anything is unclear.

I am second year PhD student working on the optimisation of the conceptual structural design in BIM. This research is a part of my PhD thesis.

***2.* Study Summary**

Structural design and analysis is an important and time-consuming process, particularly at the conceptual design stage. Decisions made at this stage can have an enormous effect on the entire project, as it becomes ever more costly and difficult to alter the choices made early on in the construction process. Hence, optimisation of the early stages of structural design can provide important efficiencies in terms of cost and time. This paper suggests a structural design optimization (SDO) framework in which Genetic Algorithms (GAs) may be used to semi-automate the production and optimisation of early structural design alternatives.

This study is concerned with the structural design process in BIM environment, which is important because this process has vital effect on the whole process of the construction.

We are seeking participants who should be able to identify the barriers and benefits of the SDO framework. Participation in the research would require you to take part in the questionnaire and take approximately 7 minutes of your time.

3. What is the purpose of the study?

The main aim of this research is to improve the early stage of conceptual structural design process in BIM environment. Therefore, conceptual SDO framework has been developed and will be validated through questionnaires in order to develop extended SDO framework based on the data received from the questionnaire.

4. Why have I been invited?

You have been invited to take part in this questionnaire based on your formal IStructE membership title (Chartered/ Associate member of the institution).

5. Do I have to take part?

No, taking part in this research is entirely voluntary. It is up to you to decide if you want to volunteer for the study. We will describe the study in this information sheet. If you agree to take part, we will then ask you to sign the attached consent form, dated May 2018, version number, 1.0.

6. What will happen to me if I take part?

Completion of questionnaires which should take approximately 10 minutes, the total duration of the research is 3 years, and total duration of the data collection is 2 months. Generally participants will be asked to answer a series of questions.

The questionnaire includes three sections as explained below:

Section 1: Demographic Information
This section asks personal information for example: what is your highest degree or years of experience. This information is necessary to analyse the data. In this section respondents will be assured that the data they share with us will not be passed on to anyone else and will not be used for any other reason. Additionally, they will be asked to feel free to leave any question blank if they are not comfortable answering them.

Section 2: Structural Design and Analysis and BIM
This section asks questions about structural design and analysis and BIM. This section helps to classify the respondents' proficiency.

Section 3: Conceptual Structural Design Optimisation (SDO) framework
This section introduces the proposed conceptual SDO framework with a brief description of the whole process. Thereafter, the respondents will be asked about their views of the proposed framework.

No publication plans yet. In the case of publishing, research publications will be Open Access (OA).

The following flowchart demonstrates the methods will be used in the research to meet the objectives

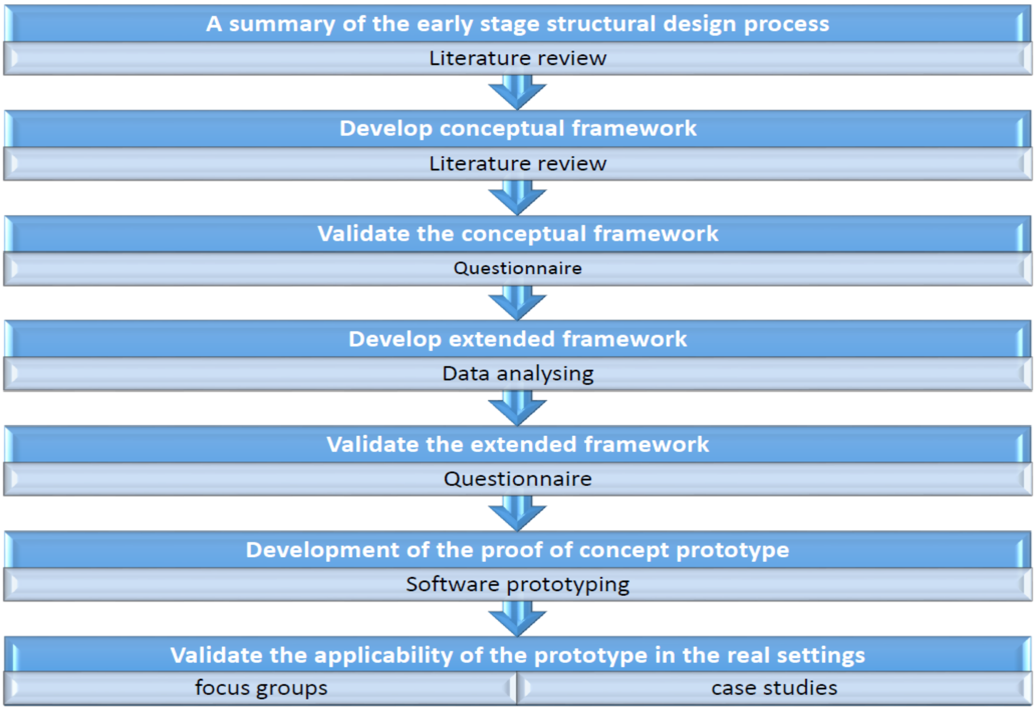


Figure 74: Research methods and objectives

7. Expenses and payments

Contribution to the research is voluntary and without recompense

8. Anything else I will have to do?

This research doesn't have further requirement.

9. What data will be collected and / or measurements taken?

The research will classify the entire questionnaire responses if the participants agreed. Thereafter, the responses will be used as validation data (qualitative and quantitative) to validate the conceptual SDO framework and develop an extended version of the SDO framework and further analysis.

10. What are the possible disadvantages, burdens and risks of taking part?

There is no known risks or disadvantages of talking part, as we strive to protect your confidentiality.

11. What are the possible advantages or benefits of taking part?

You will not receive any direct personal benefits from participating but society of the structural design and BIM may benefit from the results of this work by developing a new framework to facilitate and accelerate the process of the structural design through a semi-automatic process.

12. Will my taking part in the study be kept confidential?

Yes, your participation in the study will be kept confidential. All the information received from the participants will be anonymised, therefore those reading reports from the research will not know who has contributed to it. Moreover, except the researcher nobody else will have access to the data, which will be saved securely on password-protected laptop and stored securely for 10 years.

The data, when made anonymous, may be presented to others at academic conferences, or published as a project report, academic dissertation or in academic journals or book. It could also be made available to any commissioner or funder of the research. Anonymous data, which does not identify you, may be used in future research studies approved by an appropriate research ethics committee.

The raw data, which would identify you, will not be passed to anyone outside the study team without your express written permission. The exception to this will be any regulatory authority which has the legal right to access the data for the purposes of conducting an audit or enquiry, in exceptional cases. These agencies treat your personal data in confidence.

The raw data will be retained for up to 10 years. When it is no longer required, the data will be disposed of securely (*e.g.* electronic media and paper records / images) destroyed.

13. What will happen if I don't want to carry on with the study?

As a volunteer you can stop any participation in the questionnaire at any time, or withdraw from the study at any time before it completes, without giving a reason if you do not wish to. If you do withdraw from a study after some data have been collected you will be asked if you are content for the data collected thus far to be retained and included in the study. If you prefer, the data collected can be destroyed and not included in the study. Once the research has been completed, and the data analysed, it will not be possible for you to withdraw your data from the study.

14. What if there is a problem?

If you have a query, concern or complaint about any aspect of this study, in the first instance you should contact the researcher(s) if appropriate. If the researcher is a student, there will also be an academic member of staff listed as the supervisor whom you can contact. If there is a complaint and there is a supervisor listed, please contact the Supervisor with details of the complaint. The contact details for both the researcher and any supervisor are detailed on page 1.

If your concern or complaint is not resolved by the researcher or their supervisor, you should contact the Head of Department:

The Head of Department	Mr Andrew Packer
Department / School of…..	023 9284 2918
University of Portsmouth	sces-admin@port.ac.uk
Portland Building	
Portland Street	
Portsmouth	
PO1 3AH	

If the complaint remains unresolved, please contact:

The University Complaints Officer

023 9284 3642 complaintsadvice@port.ac.uk

15. Who is funding the research?

This research is being self-funded by the researcher.

16. Who has reviewed the study?

Research involving human participants is reviewed by an ethics committee to ensure that the dignity and well-being of participants is respected. This study has been reviewed by the xxxxx Faculty Ethics Committee and been given favourable ethical opinion. (to be added after approval)

Thank you

Thank you for taking time to read this information sheet and for considering volunteering for this research. If you do agree to participate your consent will be sought; please see the accompanying consent form. You will then be given a copy of this information sheet and your signed consent form, to keep.

Consent Form

CONSENT FORM

Title of Project: Optimisation of the conceptual structural design in BIM environment

Name and Contact Details of Researcher(s): Tofigh Hamidavi (Tofigh.hamidavi@port.ac.uk)

Name and Contact Details of Supervisor (if relevant): Dr Sepehr Abrishami (sepehr.abrishami@port.ac.uk)

University Data Protection Officer: Samantha Hill, 023 9284 3642 or data-protection@port.ac.uk

Plea

Ethics Committee Reference Number: (this may not be available at the time the form is submitted for review)

1. I confirm that I have read and understood the information sheet dated April 2018 (version 1.0) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. ☐

3. I understand that data collected during this study will be retained in accordance with the University's data retention policy and *could* also be requested by UK regulatory authorities. ☐

4. I understand that the results of this study may be published and / or presented at meetings or academic conferences, and may be provided to research commissioners or funders. I give my permission for my anonymous data, which does not identify me, to be disseminated in this way. ☐

5. I agree to the data I contribute being retained for any future research that has been given a favourable opinion by a Research Ethics Committee. ☐

6. I agree to take part in the above study. ☐

Name of Participant:	**Date:**	**Signature:**
Name of Person taking Consent:	**Date:**	**Signature:**

Note: When completed, one copy to be given to the participant, one copy to be retained in the study file

Appendix B

FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Research Degrees Operational Handbook for more information

UNIVERSITY of PORTSMOUTH

Postgraduate Research Student (PGRS) Information			Student ID:	757969
PGRS Name:	Tofigh			
Department:	SCES	First Supervisor:	Dr Sepehr Abrishami	
Start Date: (or progression date for Prof Doc students)		01/02/2017		
Study Mode and Route:	Part-time ☐ Full-time ☒	MPhil ☐ PhD ☐	MD ☐ Professional Doctorate ☐	

Title of Thesis:	Automatic integrated structural design and optimisation in BIM
Thesis Word Count: (excluding ancillary data)	41805

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	TECH 2019 - T.H – 02

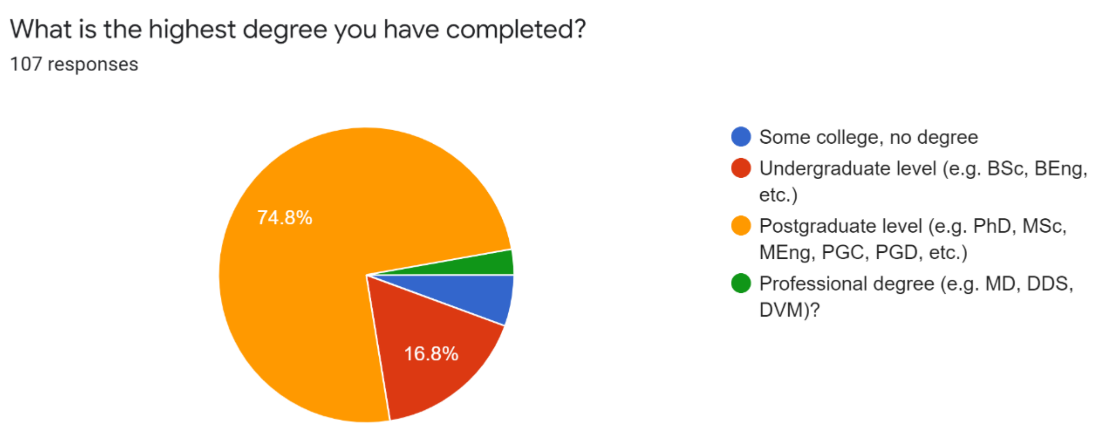
If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:

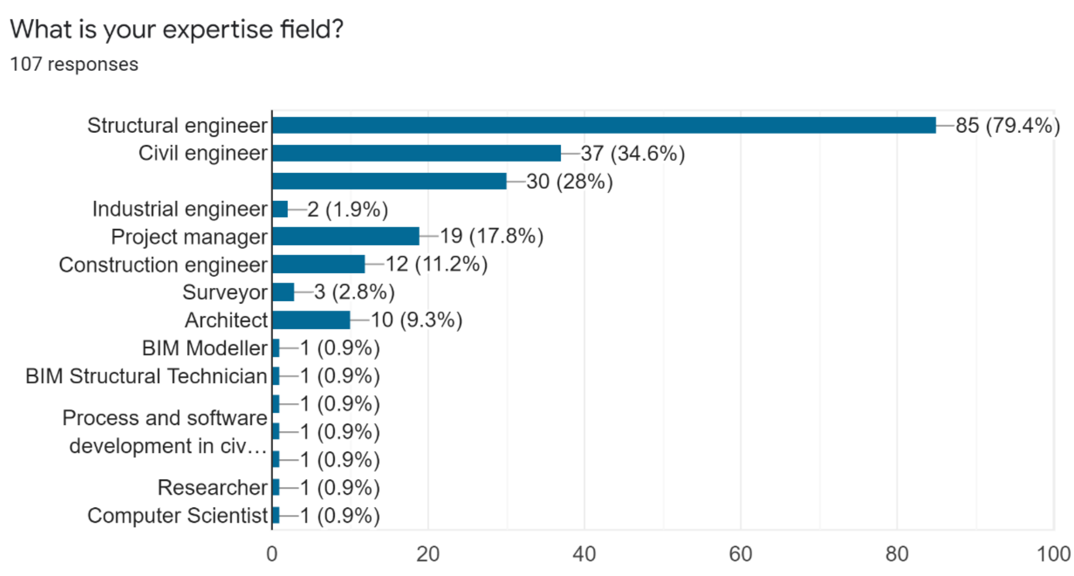
Signed (PGRS):		Date: 30/03/2020

UPR16 – April 2018

Appendix C

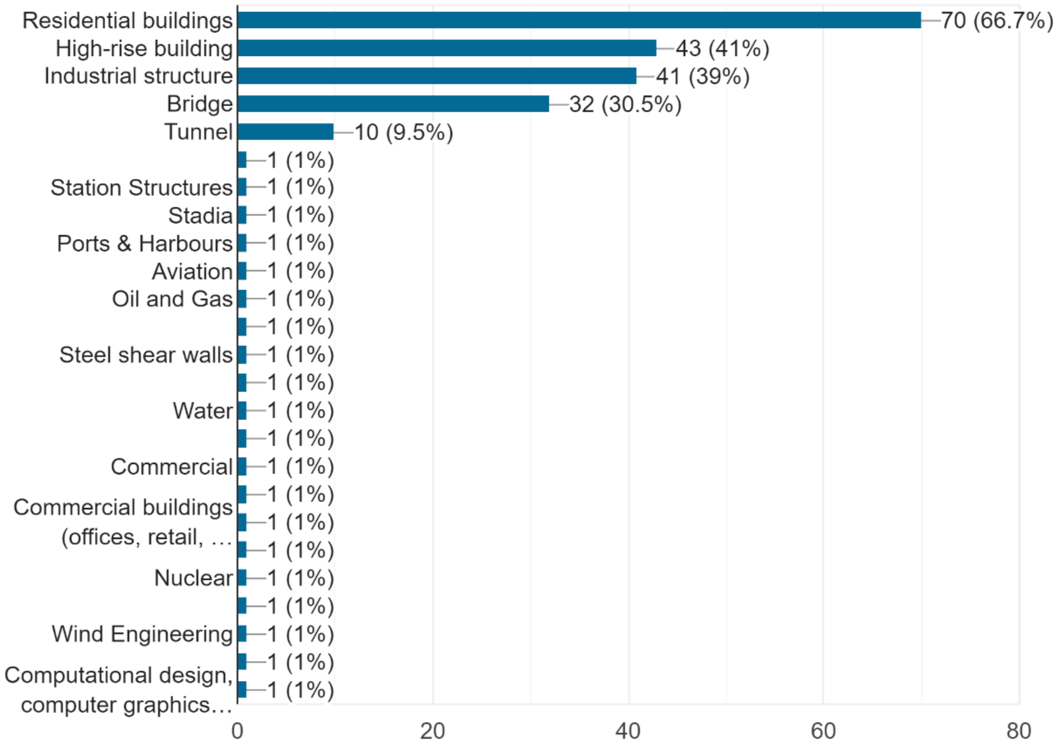
Sample of responses to the questionnaire





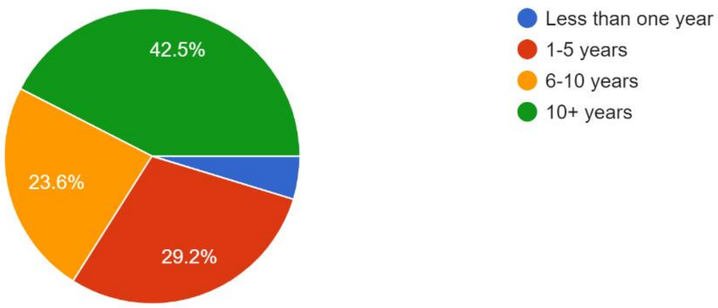
What is your area of expertise?

105 responses

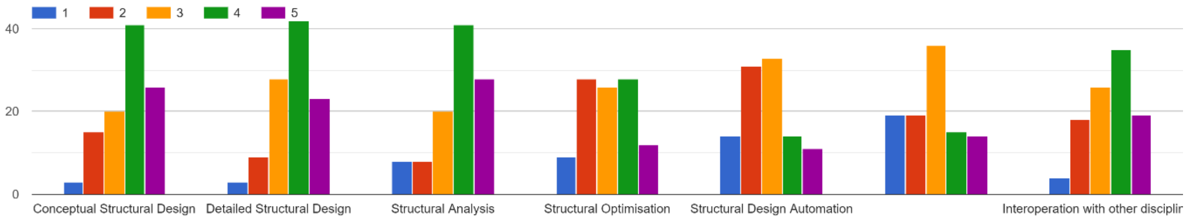


How many years experience do you have in your area of expertise?

106 responses

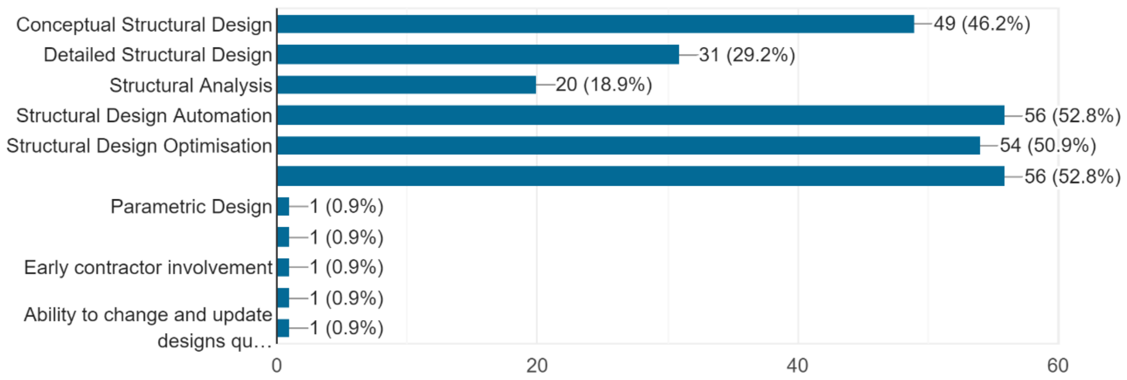


How would you rate your knowledge of the following items?(1: Minimum and 5: Maximum)



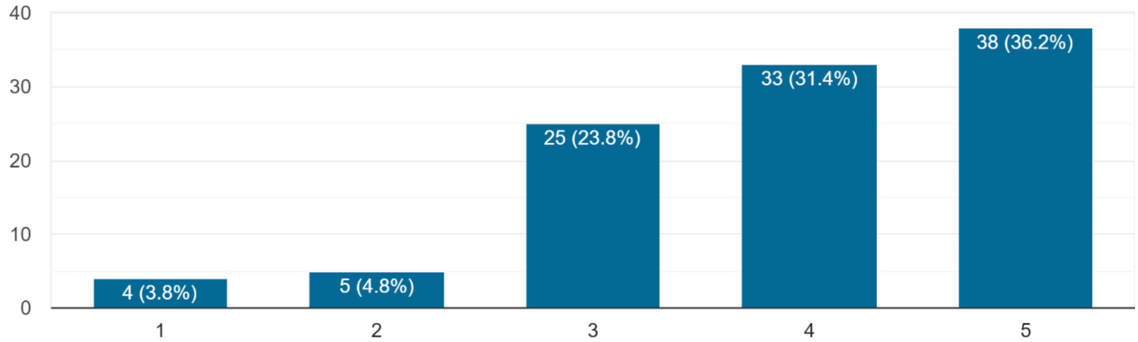
Which stage(s) of the structural design process do you think need more improvement?

106 responses



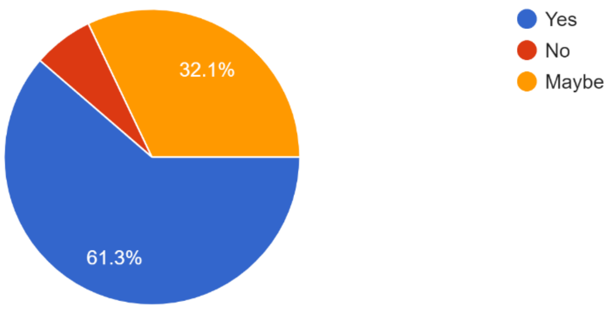
How helpful do you think having a system for generating alternative conceptual structural designs would be to choose the best structural design amon... during the early stage of the structural design?

105 responses



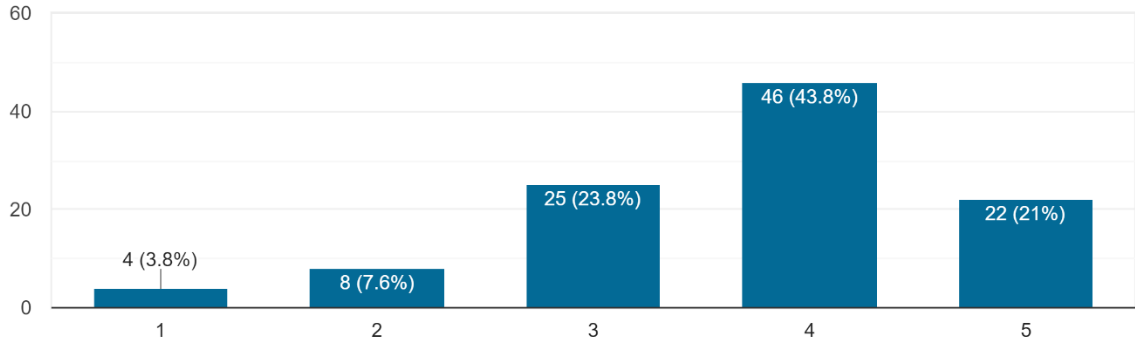
Do you think automation in the structural design and analysis can improve designers' capabilities during the early stage?

106 responses

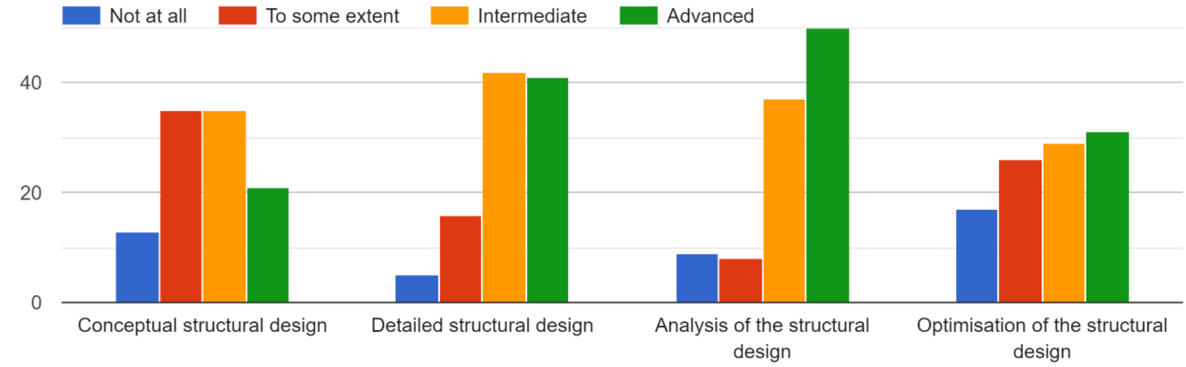


How would you rate your levels of proficiency related to Computer Skills in structural design?

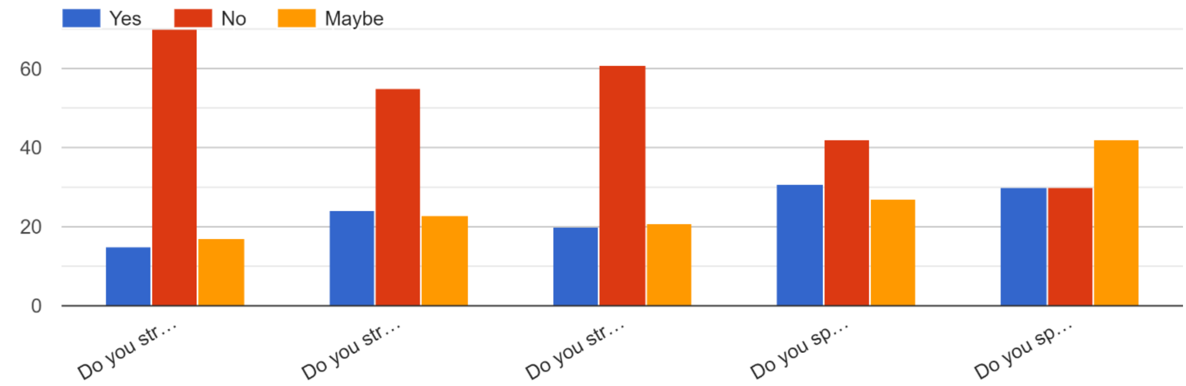
105 responses



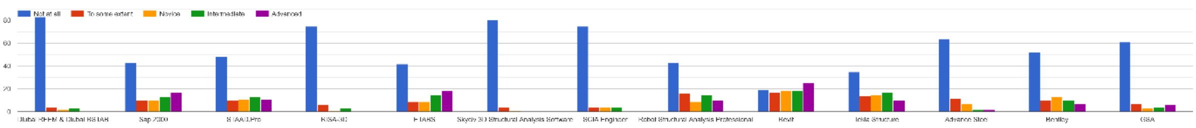
Please rate your use of computer tools at each stage of structural design and analysis process

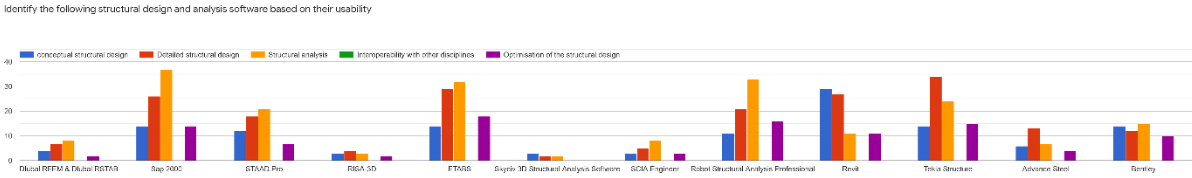


Which one of the following questions reflect your opinion of the issues raised below?



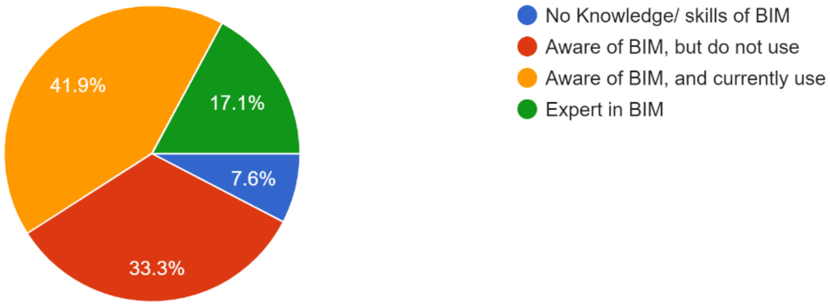
Identify the following structural design and analysis software based on your proficiency level.





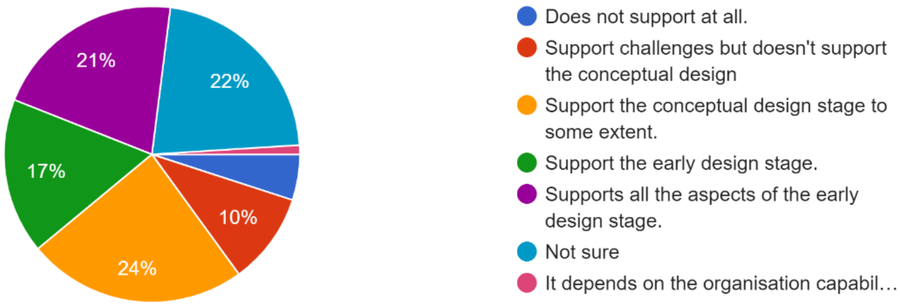
Identify your level of awareness and skills proficiency in Building Information Modelling (BIM) tools

105 responses



Based on your experience in BIM, how would you identify the current challenges at the conceptual structural stage (before the detailed stage)?

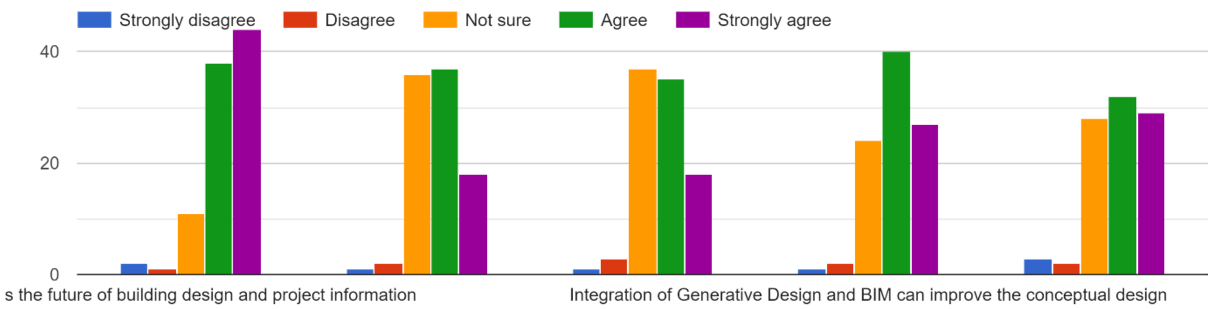
100 responses



Identify your level of awareness and skills proficiency in Generative Design.
102 responses

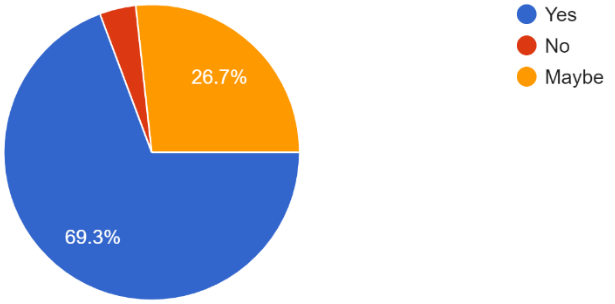
Do you think the integration of Generative Design and BIM at the early stage of structural design can improve designers' capabilities?
102 responses

Concerning the integration of BIM and Generative Design, please rank your level of agreement with the following statement



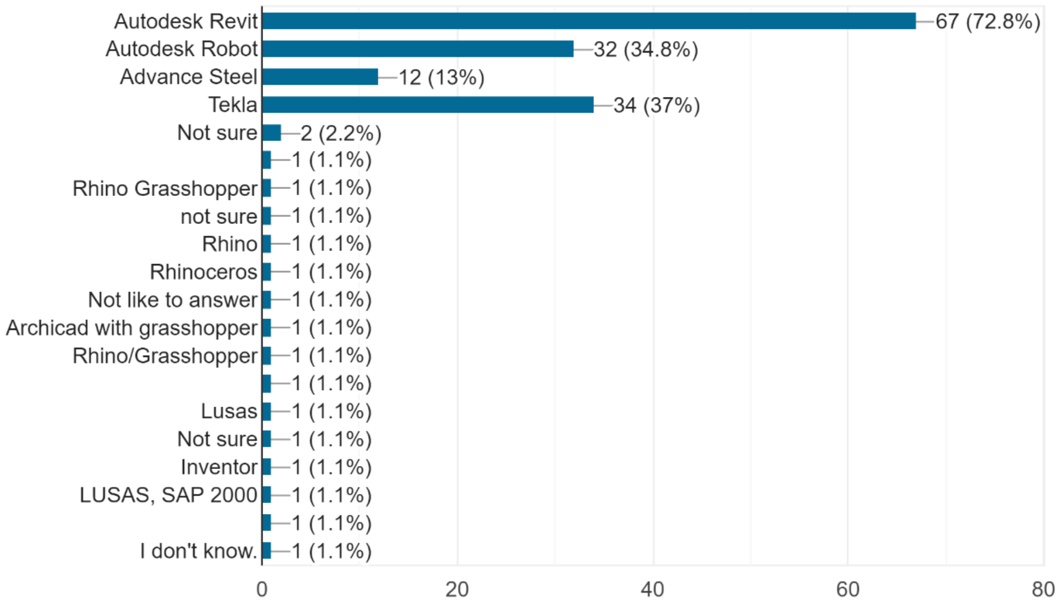
Do you think automation in the structural design and analysis in BIM can improve designers' capabilities during the early stage?

101 responses



Indicate which one of the following systems has the potential for the integrating with Generative Design

92 responses



End